SPACE-TIME DEPENDENT TRANSPORT, ACTIVATION, AND DOSE RATES FOR RADIOACTIVATED FLUIDS

By

SERGIO GAVAZZA

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

1992

To My Parents.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation and sincere thanks to the members of his supervisory committee, Dr. David E. Hintenlang, Dr. William H. Ellis, Dr. Nils J. Diaz, Dr. William E. Bolch, and Dr. Luis M. Muga, for their suggestions and willingness to assist during the development of this work.

The author is particularly thankful to Dr. David E. Hintenlang, his advisor and supervisory committee chairman, for his patient support, for his continuous and objective orientation throughout this research, for his patience in reading and correcting the drafts and the editorial modifications of this work, and for creating a harmonious work atmosphere, invaluable to the preparation of this dissertation.

Sincere thanks are extended to Dr. William H. Ellis, whose doors were always open and who was always patient, encouraging and available to discuss the project and to give valuable suggestions.

Sincere thanks are also due to Dr. Nils J. Diaz, whose comments, advice in developing the direction of the research, constructive suggestions, and patience in reading and correcting the drafts of this work were of great assistance and enriched this dissertation.

Particular thanks go to Khalid Jamil, who, among other friends, contributed to making the author's stay at the University of Florida a gratifying experience.

The author also wants to express the highest degree of appreciation to his wife, Neusa, and daughters Cristina, Cláudia and Patrícia, for their patience and support.

Finally, the author wants to express his gratitude to the Brazilian Army, which sponsored him during his graduate studies, and to the Brazilian National Development Council (Conselho Nacional de Desenvolvimento Científico e Tecnológico), which cosponsored him.

TABLE OF CONTENTS

page

ACKNOWLEDGMENTS..... iii

ABSTRACT..... vii

CHAPTERS

1 INTRODUCTION..... 1

2 REVIEW OF LITERATURE..... 6

3 THEORY AND CALCULATION METHODOLOGIES..... 14

Introduction..... 14
The Transport and Activation Methodology (TAM).... 15
Definition of the Problem..... 15
The Numerical Method..... 17
Fluid Flow Equations..... 21
Coupling Equations..... 24
Radioactivation Equations..... 28
Volumetric Source Equations..... 39
The Gamma Ray Dose Methodology (GAM)..... 41
Definition of the Problem..... 41
Buildup Factor for the Multilayered Shield... 42
Gamma Ray Dose Equivalent Rate..... 47
Numerical Solution..... 48
Computer Programs..... 49

4 RESULTS AND DISCUSSION..... 51

Sample Problems..... 51
Objectives..... 51
Limitations..... 55
Data..... 56
Activation of Air Inside a Radiation Field
(Sample Problem 1)..... 61
Problem Description..... 61
Results and Discussion..... 62
Activation of Air and Water Inside a Reactor
(Sample Problem 2)..... 72
Problem Description..... 72
Results and Discussion..... 73

Gamma Ray Dose from Radioactivated Air Moving Inside a Pipe (Sample Problem 3)..... 82
Problem Description..... 82
Results and Discussion..... 82
Summary of the Sample Problems..... 89

5 CONCLUSIONS..... 92

APPENDICES

A COMPUTER PROGRAMS RNATPA1 AND GRDOSER..... 98

B LISTING OF THE COMPUTER PROGRAM RNATPA1..... 117

C LISTING OF THE COMPUTER PROGRAM GRDOSER..... 155

D APPARATUS FOR EXPERIMENTAL MEASUREMENTS..... 172

REFERENCES..... 173

BIOGRAPHICAL SKETCH..... 176

Abstract of Dissertation Presented to the Graduate School of the University of Florida in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

SPACE-TIME DEPENDENT TRANSPORT, ACTIVATION, AND DOSE RATES FOR RADIOACTIVATED FLUIDS

By

Sergio Gavazza

December 1992

Chairperson: David E. Hintenlang
Major Department: Nuclear Engineering Sciences

Two methods are developed to calculate the space- and time-dependent mass transport of radionuclides, their production and decay, and the associated dose rates generated from the radioactivated fluids flowing through pipes. The work couples space- and time-dependent phenomena, treated as only space- or time-dependent in the open literature.

The transport and activation methodology (TAM) is used to numerically calculate space- and time-dependent transport and activation of radionuclides in fluids flowing through pipes exposed to radiation fields, and volumetric radioactive sources created by radionuclide motions. The computer program Radionuclide Activation and Transport in Pipe (RNATPA1) performs the numerical calculations required in TAM.

The gamma ray dose methodology (GAM) is used to numerically calculate space- and time-dependent gamma ray dose

equivalent rates from the volumetric radioactive sources determined by TAM. The computer program Gamma Ray Dose Equivalent Rate (GRDOSER) performs the numerical calculations required in GAM.

The scope of conditions considered by TAM and GAM herein include (a) laminar flow in straight pipe, (b) recirculating flow schemes, (c) time-independent fluid velocity distributions, (d) space-dependent monoenergetic neutron flux distribution, (e) space- and time-dependent activation process of a single parent nuclide and transport and decay of a single daughter radionuclide, and (f) assessment of space- and time-dependent gamma ray dose rates, outside the pipe, generated by the space- and time-dependent source term distributions inside of it. The methodologies, however, can be easily extended to include all the situations of interest for solving the phenomena addressed in this dissertation.

A comparison is made from results obtained by the described calculational procedures with analytical expressions. The physics of the problems addressed by the new technique and the increased accuracy versus non-space and time-dependent methods are presented. The value of the methods is also discussed. It has been demonstrated that TAM and GAM can be used to enhance the understanding of the space- and time-dependent mass transport of radionuclides, their production and decay, and the associated dose rates related to radioactivated fluids flowing through pipes.

CHAPTER 1
INTRODUCTION

The mass transport of radionuclides, their production and decay, and the associated dose rates, have been studied extensively since the early discover of radioactivity. Mankind started to study and use radiation from radionuclides in 1896 when Henry Becquerel discovered the radioactivity of uranium [1], and afterwards have increasingly created man-made radionuclides in nuclear reactors, accelerators, nuclear experiments, etc.. The development of practices of radiation protection and shielding are dependent on the knowledge of the concentration of radioactive species, their location and physical behavior.

The treatment of the activation, decay and dose rate from stationary radionuclides is well-described in the literature [2-7]. For stationary radionuclides, the activation and decay processes and the dose rates generated are governed by simple time-dependent analytical expressions.

For the case of moving fluids, simplified treatments of the activation and decay processes and of the generated dose rates assume homogeneous fluids with constant density and identical activation and decay times for all the unit volumes of the fluid. The mass transport is normally assumed to have

constant velocity and a batch process is considered for the production and decay of radionuclides. The resulting source terms in the fluid are time-dependent values assigned to specific locations [8,9].

Radionuclides are created by the bombardment of certain nuclides with suitable particles. Neutrons being electrically neutral, are ideally suited for this purpose [7]. In nuclear plants, fluids flowing through vessels or pipes may be exposed to neutron radiation fields and radionuclides can be produced. The moving radionuclides create volumetric radioactive sources along the vessels or pipes; these sources generate radiation fields and doses to equipment, man, etc..

Radiation Protection and Shielding is the area of Nuclear Engineering that deals with the protection of equipment and man against the deleterious effects of radiations. Specialists in this area are responsible for the safety aspects in the design of processes, equipment and facilities utilizing radioactive sources. When radiation damage cannot be diminished by reducing the strengths of the sources, by reducing the irradiation times, or by increasing the distance between sources and irradiated objects, shielding materials must be used to properly attenuate and absorb the emanating radiation.

The fundamental parameters governing radiation shielding designs and calculations include definition of the radioactive sources, the external radiation fields, and the required

radiation dose limits. However, in many situations, information concerning radioactive sources will not be readily available and detailed descriptions and calculations can become quite complex. Designers must make calculations using their knowledge of the physical situation modeled as some specific geometry. As an example, problems involving radioactive sources that are not constant in space and time require sophisticated calculation schemes.

An important case requiring the determination of radionuclide concentrations, distribution and dose rate is encountered in transport loops of radioactivated fluids. In this case, an accurate solution requires treatment of the coupled space-time dependence of the mass transport, irradiation and source distribution for dose calculation. This problem is addressed in this dissertation, limited by specific choices to an architecture addressable with a 80486DX IBM-compatible personal computer (486 PC).

The generic case of space-time dependent problem would consider:

a) Laminar or turbulent fluid flow in ducts with varying geometries;

b) Nonrecirculating or recirculating flow schemes;

c) Space-time dependence of the mass transport calculated as a function of the space-and time-dependent distributions of velocities and density of the fluids inside ducts;

d) Space-, time- and energy-dependent transport of neutrons through fluids moving inside ducts (i.e.,multigroup energies for neutrons);

e) Space-, time- and energy-dependent production rates of radionuclides;

f) Space- and time-dependent transport and decay of radionuclides throughout the ducts;

g) Space-, time- and energy-dependent distributions of different volumetric radioactive sources (i.e., alpha source, beta source, gamma source, etc.) throughout the ducts; and

h) Space- and time-dependent dose rates from the space-, time- and energy-dependent distributions of volumetric radioactive sources inside the ducts.

This dissertation addresses the following scope of conditions for space-time dependent transport and activation processes of fluids:

a) Laminar flow of incompressible fluid in straight pipe;

b) Nonrecirculating or recirculating flow schemes;

c) Time-independent distribution of velocities of the fluid;

d) Spatial distribution of the neutron flux is assumed known; no time dependence is considered and the neutrons are monoenergetic;

e) Single activation process of a single parent nuclide producing a single daughter radionuclide that emits gamma rays;

f) Space- and time-dependent transport and decay of a single radionuclide throughout the pipe; and

g) Space- and time-dependent gamma ray dose rate, calculated outside the pipe, from the space- and time-dependent distribution of the gamma ray volumetric sources inside of it.

The methodologies are developed for 486 PC applications to provide readily accessible calculations of the space- and time-dependent gamma ray volumetric radioactive sources created by moving radionuclides inside a pipe, the strengths of these sources, and the gamma ray dose equivalent rates created by moving radionuclides at any point outside the pipe. For dose calculations, point sources at discrete positions inside the pipe are derived from the volumetric sources. Multilayered shields can be considered between the point sources and the position of interest.

CHAPTER 2
REVIEW OF LITERATURE

In 1956, Rockwell [8] calculated the specific activity in nuclear reactor flowing coolants. Three different flow schemes were considered and water was used as coolant. Average times spent by a unit volume of water in the various parts of the reactor were considered. An analytical formula, based on these average times, was derived to calculate the typical variation of coolant activity as the coolant passes through the reactor.

Later, in 1970, Picarelli [10] derived analytical formulas to evaluate the activation of circulating cooling media. The calculations, like those from Rockwell, were based on the total cycle time and on the average time that a unit volume element spends inside a region (e.g., reflector, lower plenum, core, upper plenum, and external loop).

More recently, in 1982, Wood [9] calculated the reactor coolant activation and derived analytical formulas, still based on the average times spent by the coolant inside the different regions.

Rockwell, Picarelli and Wood all used a similar approach in their works. Since the velocity of the fluid and the geometry of the duct were not taken into account, and only

average times were considered, it was possible to derive relatively simple analytical expressions to calculate the concentrations of radionuclides in activated coolants.

Analytical expressions are not always suitable, however, for calculating the activation of moving fluids inside pipes. The use of average activation times for the different regions might not be sufficiently accurate. The geometries of the pipes, velocities, and physical properties of the fluids must be considered for an accurate representation of the physical phenomena. Iterative calculations, using numerical methods, are suitable for these cases. The solutions of the mathematical models imply solving the governing differential equations for fluid flow in control volumes inside confined domains.

Multiple literature searches were performed to identify published works related to activation and transport of radionuclides in fluids flowing inside pipes. The literature searches of unclassified nuclear information indicated that no full treatment of space-time coupled phenomena was addressed.

The results of the literature surveys confirmed that the development of the two methodologies presented in this work (transport and activation methodology and gamma ray dose methodology) would enhance the state-of-the-art for the calculation of dose rates from radioactivated fluids flowing through pipes. The transport and activation methodology (TAM) was developed to calculate space- and time-dependent transport

and activation of radionuclides inside a pipe. The gamma ray dose methodology (GAM) was developed to calculate gamma ray dose equivalent rate from moving radionuclides inside a pipe.

The starting point for developing the transport and activation methodology was the solution to a basic fluid flow problem. A literature review was done to determine the best analytical tools to use for the fluid flow description. The governing differential equations for fluid flow are well-defined in the literature, and multiple numerical solution methods are available. These are reviewed below.

In 1970, Patankar and Spalding [11] presented a general calculation procedure to calculate heat and mass transfer in boundary layers. In 1972, the same authors published a calculational procedure for heat, mass and momentum transfer in three-dimensional parabolic flows [12].

In 1980, Patankar [13] studied and discussed the numerical solutions for heat transfer and fluid flow. More recently, in 1991, he published a methodology for computation of conduction and duct flow heat transfer [14].

A general-purpose computer program for two-dimensional fluid flow and heat transfer, microCOMPACT software [15], version 2.1, was made available after 1988. This software uses the numerical techniques developed by Patankar in reference [13]. In 1982 and 1984, Lee [16,17] used the same techniques to solve the governing differential equations for fluid flow.

In this work, the method developed by the cited authors [11-16] and coded by Lee, was adopted and modified to fit the requirements of solving a basic fluid flow problem. Specifically, the discretization equations and the algorithms used to solve the discretization equations created for the numerical solutions of the governing differential fluid flow equations are the same as those used by Lee.

The other significant issues, coupled to the flow equations, are the activation of nuclides and the shielding. The activation of nuclides is well-defined in the literature. The shielding issue is discussed below.

In 1986, Gavazza [18] undertook an extensive literature review related to the evolution of methods for shielding calculation. With the development of computers and numerical methods, techniques for shielding calculation evolved from educated guesses and semiempirical methods to more rigorous and elaborate ones based on solutions to the Boltzmann transport equation and Monte Carlo treatments. The selection of a method to be used is dependent on the complexity of the problem, the accuracy required, and the time and cost. The most economical technique that provides the accuracy desired is the optimum choice; however, this is usually not an easy decision for the shielding designer.

The point-kernel technique is one of the most widely used methods for the solution of gamma ray shielding problems [18,19] and was selected as the method for this work. This

technique calculates the response of a detector positioned at a certain distance from a unitary point radioactive source. The method of the point kernel considers only the uncollided components of the gamma rays. The scattered components are handled by introducing the buildup factors.

The first source of buildup data for point isotropic and plane monodirectional radioactive sources, in homogeneous media, was provided by Goldstein and Wilkins, in 1954 [18,19]. After that, authors derived a number of empirical formulas to best fit the buildup data. Some of the commonly used formulas are the linear formula, Berger's formula, Capo's formula, and Taylor's formula [8,9,18,19].

Another difficulty that shield designers face is the buildup calculation for multilayered shields. The appropriate method to calculate buildup factors for these shielding arrangements is to solve the Boltzmann transport equation or to conduct a Monte Carlo calculation. However, the cost and complication of such elaborate methods are frequently unnecessary and time consuming in routine shielding calculations. In most practical applications, simple methods are considered accurate enough [9].

Methods to calculate buildup factors for multilayered shields are presented by Wood [9], Schaeffer [19], Bünemann and Richter [20], and Chilton et al. [21]. Some of the approaches used include the multiplication of the buildup factors of the layers, Blizzard's Method, Kalos' Formula,

Goldstein's Method of an Effective Atomic Number, Broder's Formula and Kitazume's Formula.

The multiplication of the buildup factors of the layers usually leads to overestimated buildup factors and consequently to an unnecessarily thick shield [9].

Blizzard's method takes the atomic number of the last material penetrated by the radiation and the total attenuation thickness of the shield as the arguments in entering the basic buildup factor tables. This method is easy to apply and gives reasonable results if the last layer has at least three mean-free-path lengths of thickness [9,20].

Kalos' formula considers the direction in which the radiation crosses the shield. The technique has been found to be accurate for two-layer shields of materials as diverse as water and lead [21].

Chilton et al. presents a method for laminations of two different materials. The positions of the materials are taken into account but each layer must be at least one mean-free-path length thick [21].

Goldstein's Method of an Effective Atomic Number homogenizes the shield layers and specifies a single effective atomic number for the shield. The buildup factor for the shielding arrangement depends upon the number of mean-free-path lengths penetrated by the radiation and the single effective atomic number for the shield. The total buildup

factor is determined by interpolating in the data for buildup in a single medium [9,20].

Broder's formula takes all layers into account, and the sequence in which they are penetrated by the radiation. The buildup for a layer is calculated using a simple differencing procedure. The total buildup factor is the sum of the buildup factors of the layers. Kitazume's formula modifies Broder's formula to take into account interface and last layer effects [9,20].

In all the cited methods for buildup factors of multilayered shields, it is assumed that buildup data for infinite homogeneous media are available from tables.

As mentioned, the point-kernel technique is used herein to calculate the gamma ray dose equivalent rates. This method was chosen because it provides the means for solving a variety of problems that involve distributed radioactive sources. Since activated flowing fluids inside a pipe contain radioactive sources that are not constant in space and time, the point-kernel technique becomes appropriate because it conducts calculation of the doses from radionuclides concentrated in any small control volume at any time. Berger's formula and Goldstein's Method of an Effective Atomic Number are used to calculate the buildup factors for multilayered shields.

Berger's formula was chosen because it presents a good balance between accuracy and computing complexity [9].

Goldstein's method was chosen after a comparative study (presented in Chapter 3) had been carried out to select the most appropriate technique to be used in the gamma ray dose methodology. With this method the user is able to design interpolation tables for buildup parameters to best suit the needs for solving the specific problems studied. To reduce the input data, these libraries can be incorporated into the computer program developed for the gamma ray dose methodology or stored in files to be read whenever necessary.

CHAPTER 3
THEORY AND CALCULATION METHODOLOGIES

Introduction

As pointed out in Chapter 1, the methodologies developed in this dissertation do not intend to solve the space- and time-dependent generic case of mass transport of radionuclides, their production and decay, and the associated dose rates when they are present in fluids flowing through vessels and pipes. The methodologies and conditions established for the scope of this work provide, however, adequate solutions for many practical cases and can be easily extended to include all the situations of interest. The conditions established for this work are:

a) Laminar flow of an incompressible fluid in straight pipe;

b) Nonrecirculating or recirculating flow schemes;

c) Time-independent distribution of velocities of the fluid;

d) Space-dependent distribution of a monoenergetic neutron flux;

e) Space- and time-dependent activation process of a single parent nuclide throughout the pipe where the neutron-gamma process is the activation reaction of interest;

f) Space- and time-dependent transport and decay of a single radionuclide throughout the pipe; and

g) Space- and time-dependent gamma ray dose rate, outside the pipe, from the space- and time-dependent distribution of the gamma ray volumetric sources inside of it.

In this chapter the fundamental governing equations for the fluid flow, transport and activation processes, and radiation field characteristics for the conditions specified above are described. Simultaneously, the numerical technique used to arrive at solutions to the problem are discussed.

The Transport and Activation Methodology (TAM)

TAM was developed to calculate the space- and time-dependent transport and activation of radionuclides inside a pipe.

Definition of the Problem

Radionuclides are produced through the interactions between neutrons and stable nuclides. Therefore, fluids flowing through pipes containing nuclides that interact with neutrons exhibit induced activities after exposure to neutron radiation fields. The activities induced directly by the bombardment of neutrons in flowing fluids inside vessels and pipes depend upon the characteristics of the fluids, flows, and activation interactions.

TAM considers straight pipes with part inside and part outside the radiation field. The pipe is defined by an axisymmetric coordinate system where laminar flow and no angular dependence are assumed. The flow field presents one-way flow or parabolic flow behavior [12], meaning that there is a predominant direction of flow, the diffusion of momentum, heat and mass is negligible in the predominant direction, and the downstream pressure field has little influence on the upstream flow conditions.

The density of the fluid is considered to be temperature dependent. The concentrations of the parent nuclides are expressed as a function of the density of the fluid. The neutron fluxes and the neutron activation cross sections are considered constant. The motions of the target nuclides are neglected for the activation interactions with neutrons [22].

To calculate the space- and time-dependent transport and activation of radionuclides inside a pipe, basic fluid flow equations are linked with the radioactivation equations by means of coupling equations. The coupling equations provide the space-dependent fluid mass flow rates throughout the pipe and the times spent by unit volumes of the fluid to cross the pipe at different radial positions. These variables allow the calculation of the space- and time-dependent variables performed by the radioactivation equations and volumetric source equations. This procedure ultimately determines the space- and time-dependent behavior of the transport and

activation of radionuclides in fluids flowing through pipes exposed to neutron radiation fields.

All variables are defined in the International System of units (SI). The only exception is the energy of the neutron for which millions of electron volts (MeV) are used instead of the joule (J). The final activities induced in the fluid are expressed in becquerel per cubic meter (Bq m^{-3}) and define the space- and time-dependent distribution of volumetric radioactive sources along the pipe.

The method employs steady state flow conditions. To simulate the steady state situation, a time step used to solve the governing fluid flow equations is large enough, 1.0×10^{20}s. Therefore, the transient term is not included in the governing fluid flow equations herein.

The Numerical Method

Four sets of equations are needed to calculate the space- and time-dependent transport and activation of radionuclides inside a pipe: fluid flow equations, coupling equations, radioactivation equations, and volumetric source equations. The fluid flow equations are the basic governing differential equations for continuity, momentum, and energy conservations. The coupling, radioactivation, and volumetric source equations are algebraic equations involving variables that depend upon the fluid flow characteristics and neutron radiation field.

The phenomena of interest in TAM are governed by differential equations and by algebraic equations. A solution method for TAM must initially solve a set of differential equations (the fluid flow problem) and subsequently a set of algebraic equations (the transport and activation problem). For steady two-dimensional axisymmetric laminar fluid flow in a pipe, analytical solutions for the space- and time-dependent transport and activation of radionuclides are difficult to obtain. Since numerical techniques enable the solution of difficult analytical problems, a numerical method appears to be the most appropriate solution method for TAM.

A numerical solution of a differential equation consists of a set of values at discrete positions from which the distribution of the dependent variables can be constructed. These discrete positions inside the calculation domain are called grid points. A numerical method considers as its basic unknowns the values of the dependent variable at the grid points. The method might derive a set of algebraic equations for these unknowns and solve it to provide the discrete values needed.

The algebraic equations involving the unknown values of the dependent variable at chosen grid points, named discretization equations, are derived from the differential equation governing the dependent variable. For a given differential equation, the discretization equations can be derived in many ways. A few common methods used are Taylor-

series formulation, variational formulation, method of weighted residuals, and control-volume formulation. These methods are presented and discussed in details in reference 13.

The control-volume formulation was chosen for use in TAM because its formulation is easy to understand and it lends itself to direct physical interpretation. The calculation domain is divided into a number of nonoverlapping control volumes. There is only one control volume surrounding each grid point. The differential equations are integrated over each control volume to provide the discretization equations containing the values of the dependent variables for all the grid points. The discretization equations obtained in this manner express the conservation principle for the dependent variables for the finite control volumes and, of course, imply that the integral conservation principle is satisfied over the whole calculation domain. In TAM, this can be seen as the integral conservation of mass, momentum and energy throughout the pipe. Moreover, the control-volume formulation is the most adequate process to describe the other physical phenomena occuring in TAM and GAM. The control-volume formulation used in this work is described below.

The internal volume of the pipe defines the calculation domain. An axisymmetric coordinate system is used. The x axis coincides with the centerline of the pipe and the y axis is perpendicular to this line. The calculation domain is

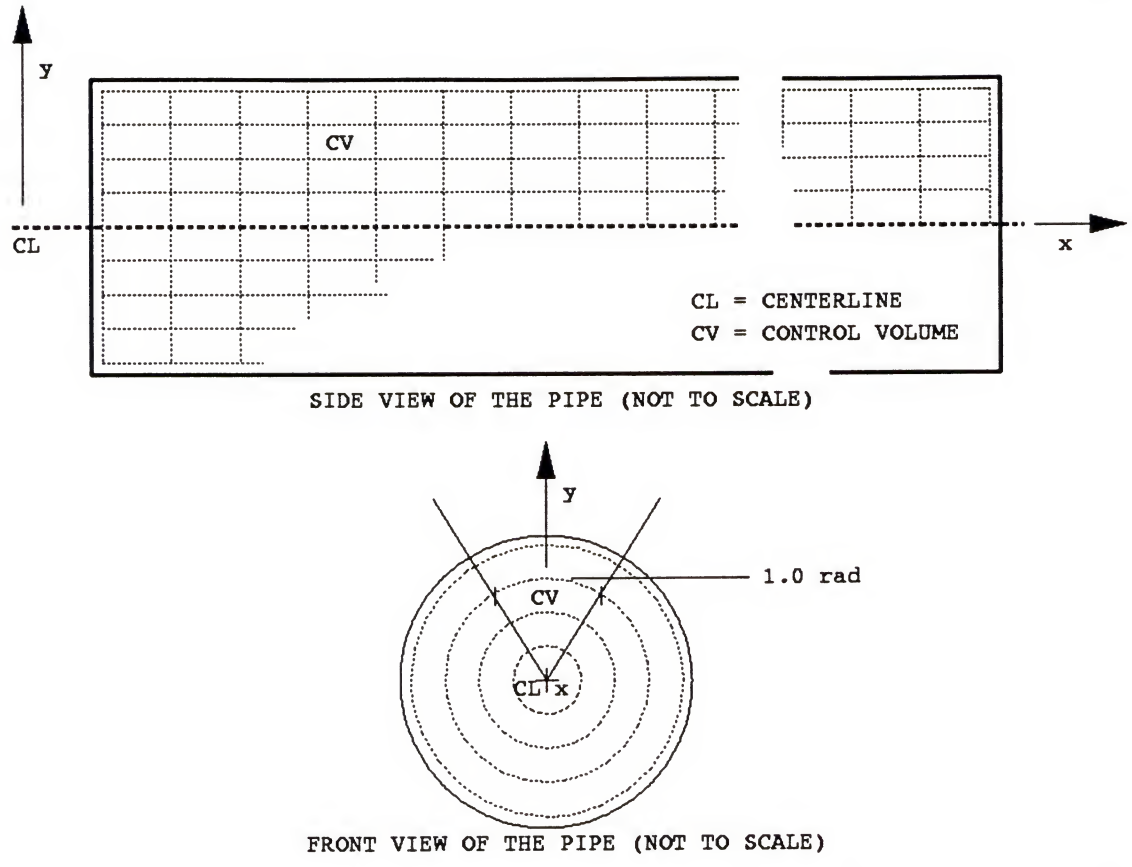


Figure 3-1. Control volumes and axes x and y of the axisymmetric coordinate system used in the calculation domain defined by the internal volume of the pipe.

divided into control volumes as shown in Fig. 3-1. The control volumes have 1.0 radian of width in the angular direction. Each control volume is constructed around a grid point defined by a pair of values x and y. A grid point is defined by a pair of indexes i and j. The grid locations in the x and y directions are denoted by i and j, respectively. Then, herein, the indexes i and j will be used to identify a grid point, the control volume surrounding this grid point, and the value of a variable at this grid point.

Fluid Flow Equations

Governing Equations. The governing differential equations for fluid flow that model the axisymmetric laminar flow of an incompressible fluid at normal pressure flowing in a pipe are:

a) mass conservation:

$$\frac{\partial}{\partial x}(\rho u) + \frac{1}{y}\frac{\partial}{\partial y}(y\rho v) = 0 \qquad (3\text{-}1)$$

b) momentum conservation:

x-direction (i-direction)

$$\rho u\frac{\partial u}{\partial x} + \rho v\frac{\partial u}{\partial y} = \frac{\partial}{\partial x}(\mu\frac{\partial u}{\partial x}) + \frac{1}{y}\frac{\partial}{\partial y}(\mu y\frac{\partial u}{\partial y}) - \frac{\partial p}{\partial x} \qquad (3\text{-}2)$$

y-direction (j-direction)

$$\rho u\frac{\partial v}{\partial x} + \rho v\frac{\partial v}{\partial y} = \frac{\partial}{\partial x}(\mu\frac{\partial v}{\partial x}) + \frac{1}{y}\frac{\partial}{\partial y}(\mu y\frac{\partial v}{\partial y}) - \frac{\partial p}{\partial y} + S_v \qquad (3\text{-}3)$$

c) energy conservation:

$$\rho u\frac{\partial h}{\partial x} + \rho v\frac{\partial h}{\partial y} = \frac{\partial}{\partial x}(\frac{k}{c_p}\frac{\partial h}{\partial x}) + \frac{1}{y}\frac{\partial}{\partial y}(\frac{k}{c_p}y\frac{\partial h}{\partial y}) \qquad (3\text{-}4)$$

In Eqs. (3-1) to (3-4), ρ is the density of the fluid, u is the velocity component in the x direction, v is the velocity component in the y direction, p is the pressure, h is the specific enthalpy, k is the thermal conductivity, c_p is the constant-pressure specific heat, and S_v is the source term for the momentum equation in the y direction and equal to $-(\mu v)/y^2$.

The density of the fluid is considered to be temperature dependent. With this assumption, the density is calculated by

$$\rho_{i,j} = \frac{\rho_{ref} T_{ref}}{T_{i,j}} \qquad (3\text{-}5)$$

where ρ_{ref} and T_{ref} are the density and temperature of reference and $T_{i,j}$ is the local temperature.

The viscosity, constant-pressure specific heat, and thermal conductivity of the fluid are considered constant in the processes. With c_p constant, the enthalpy is equal to $c_p T$ and the temperature T can be calculated from Eq. (3-4).

The solutions of Eqs. (3-1) to (3-5) provide the distributions of density, velocities, and temperature throughout the calculation domain.

Numerical Solution. The governing differential equations for fluid flows are solved by using the subroutine FFLOW of the computer program RNATPA1, which is presented in Appendices A and B. The discretization equations and the algorithms used in that subroutine to solve the discretization equations are discussed in details by Patankar in reference 13, and coded by Lee in reference 16. The sequence of operations, in terms of the main calculation steps are:

a) Guess the initial values of all the dependent variables (ρ, u, v, T and p).

b) Solve the momentum equations to obtain the first set of velocities u and v.

c) Solve the pressure-correction equation to find the correction values for the pressures guessed in step a. The pressure-correction equation is derived from the continuity equation.

d) Calculate the corrected pressure field.

e) Calculate the corrected velocity fields.

f) Solve the energy equation to obtain the temperature field.

g) Solve the density equation, Eq. (3-5), to obtain the density field.

h) Consider the corrected pressure field as the new guessed pressure field, return to step b, and repeat the whole procedure until a converged solution is obtained.

Initial values of the dependent variables needed in step a of the sequence of operations to solve the governing differential fluid flow equations have to be supplied only for the velocities $u_{i,j}$ and $v_{i,j}$, and for the temperatures $T_{i,j}$. The initial densities $\rho_{i,j}$ of the fluid are expressed by Eq. (3-5) and the initial pressures $p_{i,j}$ are handled internally in the computational program.

The fluid flow equations provide for the density $\rho_{i,j}$, the fluid velocities $u_{i,j}$ and $v_{i,j}$, and the temperature $T_{i,j}$ for each control volume. Figure 3-2 shows the positions in which these variables are calculated in each control volume. The density and the temperature are calculated at the grid point inside

the control volume. The velocities are calculated along the grid lines at the interfaces of the control volume.

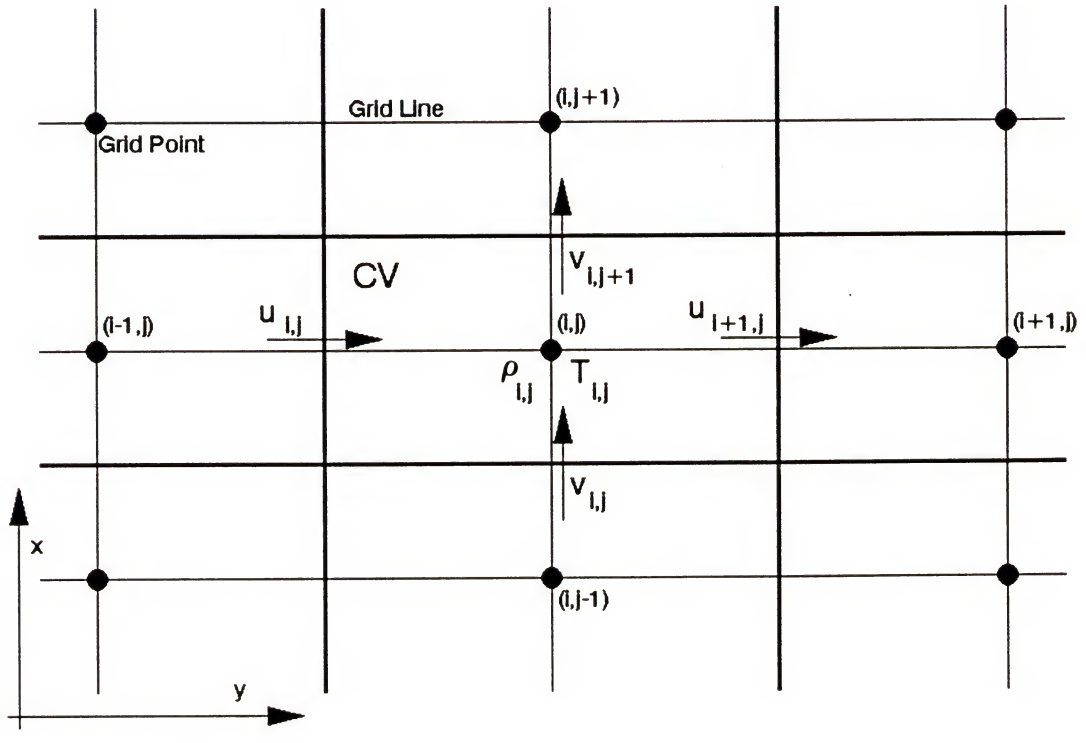


Figure 3-2. Positions in the control volume (CV) in which the density, velocities, and temperature, calculated by the fluid flow equations, are considered in TAM.

Coupling Equations

Governing Equations. The set of governing coupling equations used in TAM are:

a) fluid mass flow rate in the x direction:

$$\dot{m}_{i,j} = \rho_{i,j} A_{i,j} \overline{u}_{i,j} \qquad (3\text{-}6)$$

b) fluid mass flow rate difference in the x direction:

$$\Delta \dot{m}_{i,j} = \dot{m}_{i+j} - \dot{m}_{i,j} \tag{3-7}$$

c) fluid mass flow rate transferred to or from the control volume in the y direction:

$$\dot{m}'_{i,j} = \dot{m}_{i+1,j} - \dot{m}_{i,j} + \dot{m}'_{i,j+1} \tag{3-8}$$

d) time spent inside the control volume (dwell time):

$$t_{i,j} = \frac{w_{i,j}}{\bar{u}_{i,j}} \tag{3-9}$$

In Eqs. (3-6) to (3-9), $A_{i,j}$ is the area of the face of the control volume perpendicular to the x direction, $\bar{u}_{i,j}$ is the interpolated velocity in the x direction at the grid point, and $w_{i,j}$ is the width of the control volume in the x direction.

The fluid mass flow rate transferred to or from the control volume in y direction, calculated in Eq. (3-8), can be positive or negative. When $\dot{m}'_{i,j}$ is positive it means that mass is transferred to the control volume. When it is negative the opposite occurs and mass is transferred from the control volume.

The main purpose of the coupling equations is to determine the space-dependent fluid mass flow rate transferred to or from the control volume in the y direction and the time spent by the fluid inside the control volume (dwell time) from which the time- and space-dependent variables are coupling

between the fluid flow and the radioactivation equations. These tasks are numerically performed as explained below.

Numerical Solution. Linear interpolation is used to find the x-direction velocities at the grid points. The interpolated velocities $\bar{u}_{i,j}$ at the grid points (i,j) inside the control volumes are derived from the velocities $u_{i,j}$ and $u_{i+1,j}$, shown in Fig. 3-2, the distances $x1_i$ from the upstream face of the control volumes to the grid points, shown in Fig. 3-3, and the widths of the control volumes in the x direction. The expression for this interpolation is

$$\bar{u}_{i,j} = u_{i,j} + (u_{i+1,j} - u_{i,j})\left(\frac{x1_{i,j}}{w_{i,j}}\right) . \qquad (3\text{-}10)$$

The fluid mass flow rates in the x direction are calculated by Eq. (3-7).

Corrections are introduced to keep the total fluid mass flow rates $\dot{M}_i$ constant along the stations. A station is defined by all the control volumes with the same index i. The set of equations solved to perform the corrections are

$$\dot{M}_i = \sum_{j=1}^{m1} \dot{m}_{i,j} \quad , \qquad (3\text{-}11)$$

$$\Delta\dot{M}_i = \dot{M}_i - \dot{M}_1 \quad , \qquad (3\text{-}12)$$

and

$$cf_{i,j} = \Delta\dot{M}_i \frac{\dot{m}_{i,j}}{\dot{M}_i} . \qquad (3\text{-}13)$$

In Eq. (3-11), *m1* is the total number of control volumes in a station. In Eq. (3-12), $\Delta\dot{M}_i$ are small differences between the fluid mass flow rates at station i and at station 1, the entrance of the pipe, introduced by the numerical nature of the solutions. These small differences are due to the precision of the variables and the round off error of the values in the computer program. In Eq. (3-13), $cf_{i,j}$ are the correction factors for the fluid mass flow rates in the control volumes.

Thereafter, the corrected x-direction fluid mass flow rates $\dot{m}_{i,j;new}$, the corrected x-direction velocities $\overline{u}_{i,j;new}$, the y-direction fluid mass flow rates $\dot{m}'_{i,j}$ transferred to or from the control volumes, and the times $t_{i,j}$ spent inside the control volumes are calculated from the expressions

$$\dot{m}_{i,j;new} = \dot{m}_{i,j} - cf_{i,j} \quad , \tag{3-14}$$

$$\overline{u}_{i,j;new} = \frac{\dot{m}_{i,j;new}}{\rho_{i,j} A_j} \quad , \tag{3-15}$$

$$\dot{m}'_{i,j} = \dot{m}_{i+1,j;new} - \dot{m}_{i,j;new} + \dot{m}'_{i,j+1} \quad , \tag{3-16}$$

and

$$t_{i,j} = \frac{w_{i,j}}{\overline{u}_{i,j;new}} \quad . \tag{3-17}$$

Figure 3-3 shows the positions, in the control volume, in which the x-direction interpolated velocity, the x-direction fluid mass flow rate, and the y-direction fluid mass flow rate

transferred to or from the control volume,calculated by the coupling equations, are considered in TAM. The coupling equations are solved by using the subroutine ACTRA of the computer program RNATPA1.

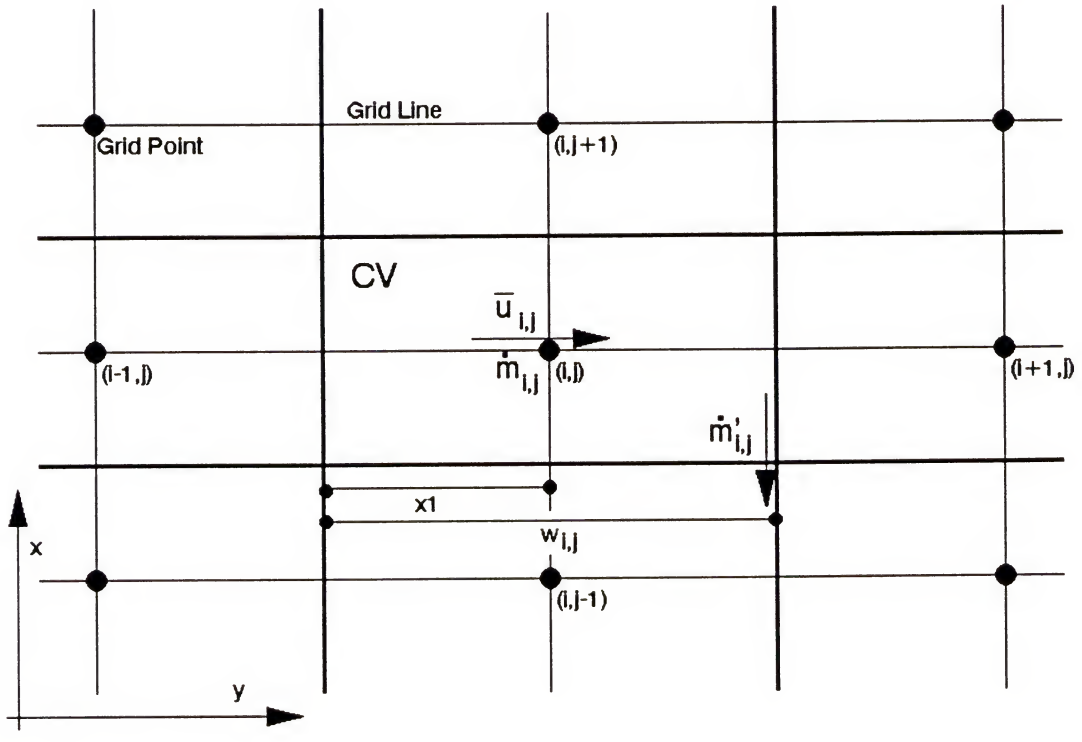


Figure 3-3. Positions in the control volume (CV) in which the interpolated velocity, the mass flow rate, and the mass flow rate transferred to or from the control volume, calculated by the coupling equations, are considered in TAM.

Radioactivation Equations

Governing Equations. The radioactivation equations calculate the space- and time-dependent transport and activation of radionuclides in fluids flowing inside pipes.

The governing radioactivation equations are:

a)final concentration of radionuclides inside a control volume:

$$N_{i,j,t_f} = \frac{1}{\lambda} \phi_{i,j} f \rho_{i,j} \sigma (1 - e^{-\lambda t_{i,j}}) + No_{i,j,t_{act}} e^{-\lambda t_{i,j}} \qquad (3\text{-}18)$$

b) concentration of radionuclides transferred from a control volume:

$$NC_{i,j,t_f} = \frac{\dot{m}'_{i,j}}{\dot{m}_{i,j}} N_{i,j,t_f} \qquad (3\text{-}19)$$

In Eq. (3-18), λ is the disintegration constant of the daughter radionuclides, $\phi_{i,j}$ is the monoenergetic neutron flux, f is a multiplication factor applied to the density of the fluid to provide the concentration of parent nuclides, σ is the neutron activation cross section of the parent nuclides for the monoenergetic neutrons involved in the process, and $No_{i,j,t_{act}}$ is the concentration of radionuclides transferred from the previous control volumes. The time t_{act} is the time elapsed since the beginning of the activation process. The time t_f is equal to $t_{act}+t_{i,j}$. The time $t_{i,j}$ is the time that a unit volume of the fluid spends inside the control volume and is provided by Eq. (3-9) of the set of governing coupling equations.

In Eq. (3-19), $\dot{m}'_{i,j}$ is the fluid mass flow rate transferred from the control volume in the y direction and $\dot{m}_{i,j}$ is the fluid mass flow rate out of the control volume in

the x direction. These variables are provided by Eqs. (3-6) and (3-8) of the set of governing coupling equations.

The mass transport and decay of daughter radionuclides and the mass transport and activation of parent nuclides occur simultaneously inside a control volume. These processes depend upon the time that a unit volume of the fluid spends inside the control volume. This time, provided by the coupling equations, is not constant and depends on the spatial position of the control volume inside the pipe.

It is important to understand that the time spent by a unit volume of the fluid inside a control volume is the same as the time that the parent nuclides and the daughter radionuclides, transported by the fluid mass flow, spend inside the control volume. The radionuclides present in the fluid at the entrance of the control volume are transported until the exit from it. During the transportation time, the radionuclides experience decay. The parent nuclides are transported for the same period of time inside the control volume; during this time they experience activation. Equation (3-18) governs both processes.

The initial concentration of radionuclides $No_{i,j,t_{act}}$ is calculated from the concentrations of radionuclides transferred from the neighboring control volumes at the upstream station. To derive an analytical expression to exactly calculate these contributions is either very difficult or impossible. To numerically account for the systematic

transfer of unit volumes, and using conservation of mass, once the radionuclides are distributed throughout the mass of the fluid, the concentration of radionuclides inside a control volume decreases whenever it loses a certain amount of mass and will increase if the opposite process occurs. Based on these considerations, TAM establishes that the concentration of radionuclides transferred from a control volume in the y direction is proportional to the mass flow rate transferred from the control volume in the same direction. In this way, the governing equation used to calculate the transfer of radionuclides from a control volume is the Eq. (3-19).

Equations (3-18) and (3-19) are the basic equations used in TAM to calculate the space- and time-dependent transport, activation and decay processes inside a control volume and, consequently, throughout the pipe. Once $No_{i,j,t_{act}}$ is found, the solution is immediate, but to derive a space- and time-dependent analytical expression for $No_{i,j,t_{act}}$ calculation is a very difficult or impossible task. It is therefore most appropriate to solve this problem numerically. The numerical procedures used in TAM for this purpose are discussed below with emphasis on a physical understanding of the process.

Numerical Solution. In the numerical solution adopted in TAM, two types of fluid flow schemes are considered: nonrecirculating and recirculating. Figures 3-4 and 3-5 show the flow schemes for nonrecirculating and recirculating fluids, respectively.

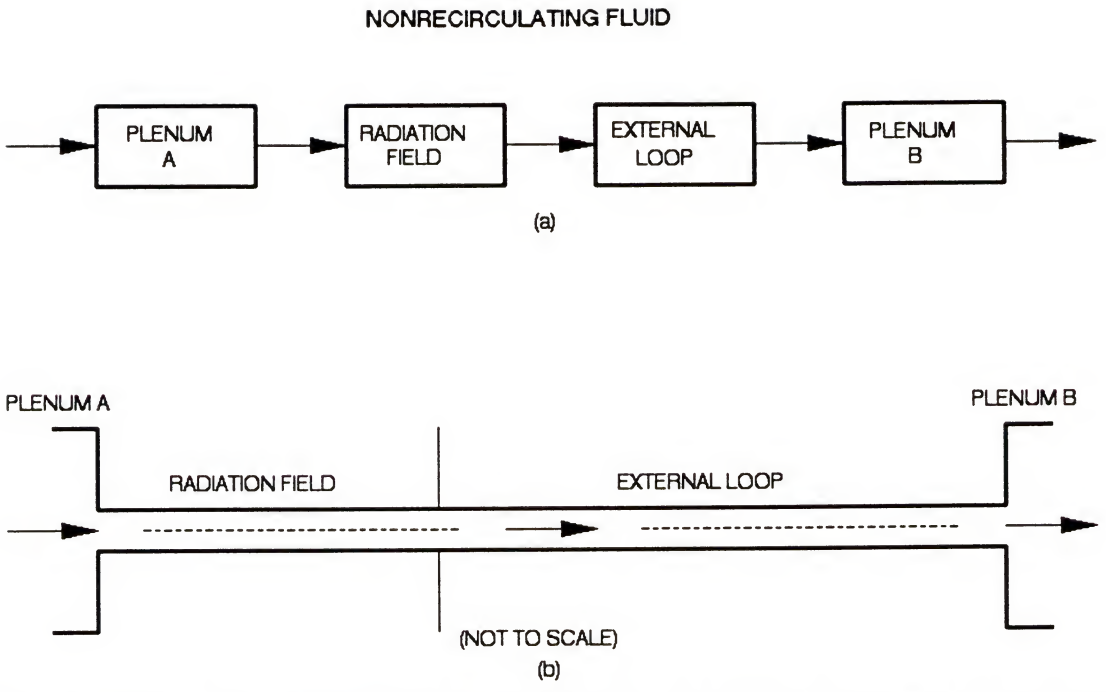


Figure 3-4. Nonrecirculating fluid. (a) Flow scheme; (b) Pipe and flow scheme in TAM.

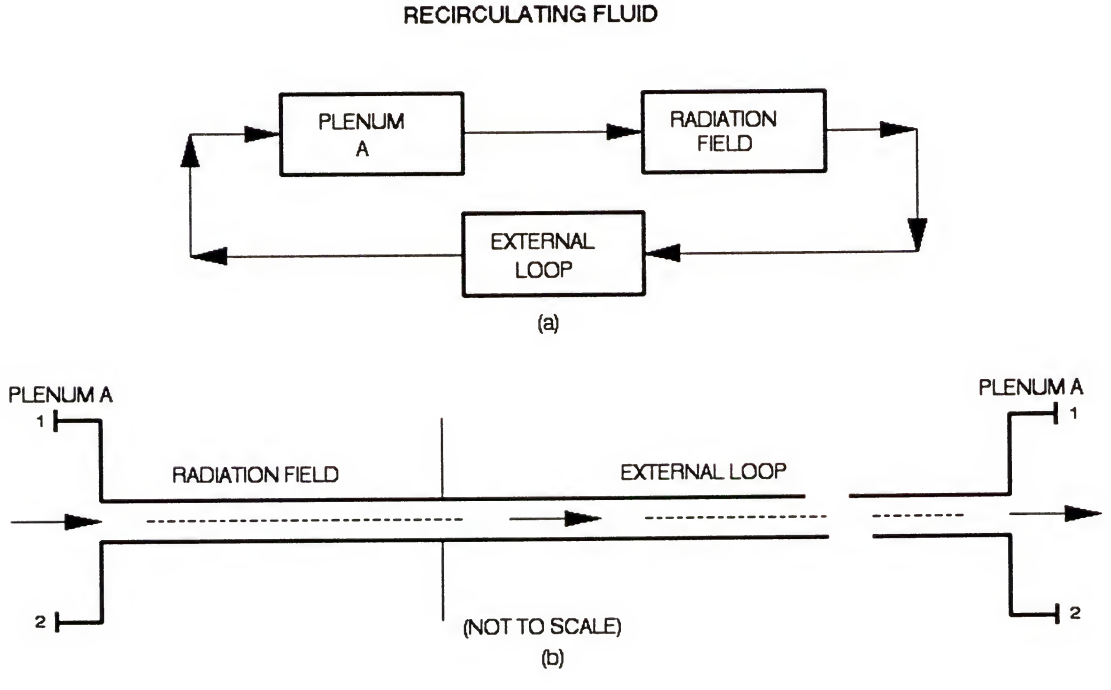


Figure 3-5. Recirculating fluid. (a) Flow scheme; (b) Pipe and flow scheme in TAM.

Two activation scenarios are considered: the space- and cycle-dependent activation, and the space- and time-dependent activation. This differentiation has only didactic purposes. In reality, as will be seen below, the cycle-dependent activation is a variation of the time-dependent activation. In both cases the space dependence is defined by the fact that the variables are calculated at discrete positions inside the calculation domain.

To compute the cycle-dependent activation or the time-dependent activation, the motion of a unit volume of the fluid inside the pipe needs to be considered. This motion is intrinsically related to the fluid mass transport in the pipe.

The times that are required for a unit volume of the fluid to cross the pipe vary and depend upon the row of control volumes (control volumes having the same index j) in which it is travelling. The time spent by a unit volume of fluid to cross the pipe in the row of control volumes closest to the boundary is greater than the time spent by a unit volume in the row of control volumes closest to the centerline. This occurs because the velocities of the fluid closer to the wall are slower than the velocities closer to the centerline. The highest velocities occur in the centerline of the pipe.

Based on this behavior of the fluid flow, six different variables (i.e., t_{act}, $t_{i,j}$, $t1_{i,j}$, $t2_{j}$, $t3_{i,j}$, and $t4_{j}$) are considered in the activation scenarios. They are called time

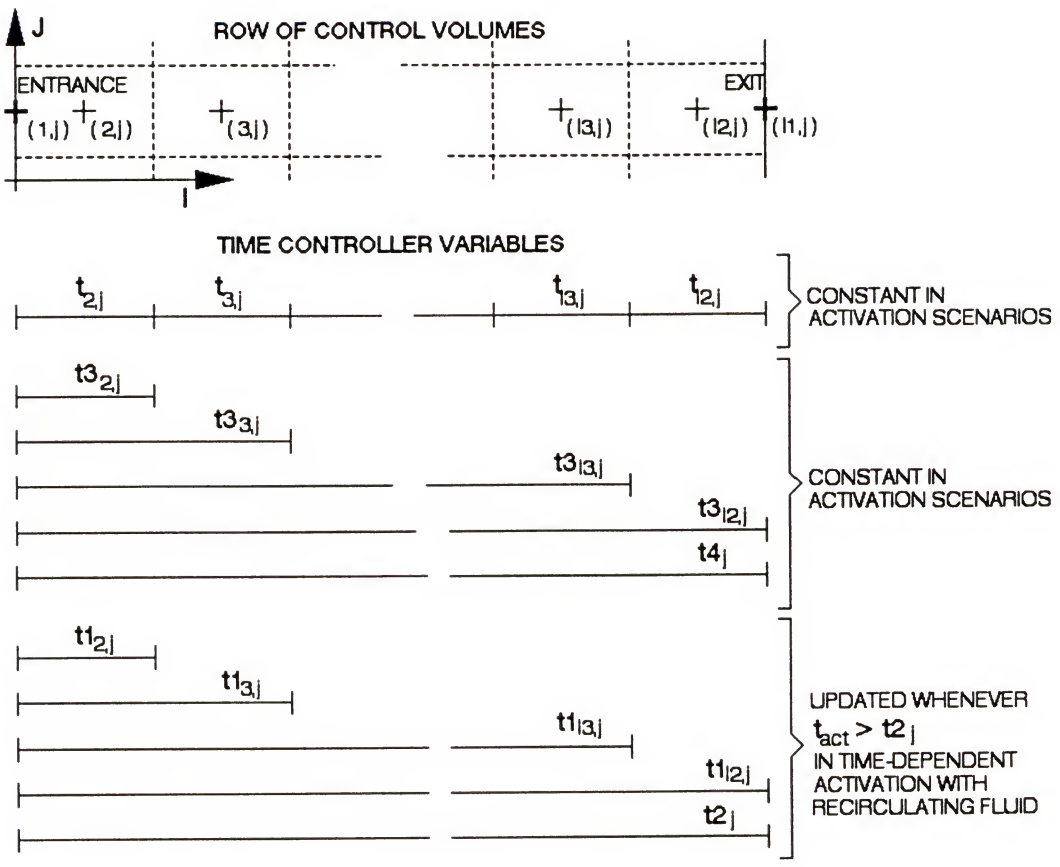


Figure 3-6. Diagram for the time controller variables in TAM.

controller variables and are explained below. Figure 3-6 shows a diagram for these variables.

t_{act} is the activation time. It refers to the time elapsed after the beginning of the activation process.

$t_{i,j}$ are the times spent by unit volumes of the fluid inside the control volumes. They are provided by the solution of the coupling equations.

$t1_{i,j}$ are the times spent by unit volumes of the fluid to reach the end of the control volumes, starting from the entrance of the pipe, travelling in the same row of control

volumes, with recirculating fluid and time-dependent activation.

$t2_j$ are the times spent by unit volumes of the fluid to reach the exit of the pipe, starting from the entrance of the pipe, travelling in the same row of control volumes, with recirculating fluid and time-dependent activation.

$t3_{i,j}$ are the times required by unit volumes of the fluid to reach the end of the control volumes, starting from the entrance of the pipe, travelling in the same row of control volumes for a nonrecirculating fluid.

$t4_j$ are the times required by unit volumes of the fluid to reach the exit of the pipe, travelling in the same row of control volumes, and nonrecirculating fluid.

For the two types of fluid flow schemes, the expressions to calculate the different times are

$$t1_{i,j} = \sum_{i=1}^{i} t_{i,j} \ , \tag{3-20}$$

$$t2_j = t1_{11,j} \ , \tag{3-21}$$

$$t3_{i,j} = t1_{i,j} \ , \tag{3-22}$$

and

$$t4_j = t2_j \ . \tag{3-23}$$

The times $t_{i,j}$, $t3_{i,j}$ and $t4_j$ are constant and independent of the activation scenario.

For a recirculating fluid and $t_{act} > t2_j$, the times $t1_{i,j}$ and $t2_j$ are updated using the equations

$$t1_{i,j;new} = t2_{j;old} + t3_{i,j} \qquad (3\text{-}24)$$

and

$$t2_{j;new} = t2_{j;old} + t4_j \ . \qquad (3\text{-}25)$$

Figure 3-6 shows the time controller variables that are constant and those that are updated according to the activation scenario and type of fluid flow scheme.

In the calculation procedure, the existing concentration of radionuclides in the control volumes are considered as the previous concentrations $N_{i,j;pre}$. When the fluid experiences activation, the previous concentrations change. Thus, the final concentrations of radionuclides $N_{i,j}$ in the control volumes are calculated. If the fluid does not recirculate, the final concentrations $N_{i,j}$ will not change. If the fluid recirculates, the actual $N_{i,j}$ will be the $N_{i,j,pre}$ for the next cycle (in the case of cycle-dependent activation) or for the next time step (in the case of time-dependent activation), and the new final concentrations of radionuclides will be calculated in the control volumes.

In the activation process, the concentrations of radionuclides in the control volumes at the last calculation station (exit of the pipe) are not equal. Then, it is assumed that the fluid is mixed before being recirculated. This

procedure enables one to consider that the concentrations of radionuclides in the control volumes at the first calculation station (entrance of the pipe) are equal for the case of recirculating fluid.

Since the nonrecirculating fluid, in which the unit volumes cross the pipe just one time (one-pass flow), can be considered as a particular case of the recirculating fluid, the following explanations will refer only to the recirculating fluid.

In the cycle-dependent activation, the calculation procedure assumes that the processes occuring in each cycle are similar to those occuring in a one-pass flow. Thus, a cycle-dependent activation scenario of a recirculating fluid can be interpreted as the activation experienced by the fluid after successive one-pass flows through the pipe. At the end of each cycle the fluid is mixed and recirculated.

For time-dependent activation, the calculation procedure assumes that after each time step, the fluid is mixed and the recirculation is immediate. This assumption is more realistic than the assumption used in the cycle-dependent activation.

In the cycle-dependent activation, the final concentrations of radionuclides inside the control volumes, $N_{i,j}$, are calculated for each cycle. In the time-dependent activation, first the time controller variables are checked. When $t_{act} < t1_{i,j}$, the previous concentration of radionuclides $N_{i,j;pre}$ is kept as $N_{i,j}$ in the control volume. When $t_{act} \geq t1_{i,j}$,

the final concentration of radionuclides $N_{i,j}$ is calculated for the control volume.

In both activation scenarios, the calculation of the final concentration of radionuclides inside a control volume is performed in the same way. For this reason the independent variable t_{act} used as index in the governing equation (3-19) was dropped from Eqs. (3-26) to (3-32) below. For each cycle or each activation time, the initial concentration of radionuclides $NI_{i,j}$ at the entrance of a control volume is computed from the concentrations transferred from the left, upper, and lower control volumes, $N_{i-1,j}$, $NU_{i-1,j+1}$, and $ND_{i-1,j-1}$, respectively, at the upstream station, using the governing equation (3-19). The following set of equations performs these calculation:

$$NU_{i-1,j+1} = -\left(\frac{\dot{m}'_{i-1,j+1}}{\dot{m}_{i-1,j+1}}\right) N_{i-1,j+1} , \qquad \dot{m}'_{i-1,j+1} < 0 ; \tag{3-26}$$

$$NU_{i-1,j+1} = 0 , \qquad \dot{m}'_{i-1,j+1} = 0 ; \tag{3-27}$$

$$NU_{i-1,j+1} = -\left(\frac{\dot{m}'_{i-1,j+1}}{\dot{m}_{i-1,j}}\right) N_{i-1,j} , \qquad \dot{m}'_{i-1,j+1} > 0 ; \tag{3-28}$$

$$ND_{i-1,j-1} = \left(\frac{\dot{m}'_{i-1,j}}{\dot{m}_{i-1,j}}\right) N_{i-1,j} , \qquad \dot{m}'_{i-1,j} < 0 ; \tag{3-29}$$

$$ND_{i-1,j-1} = 0 , \qquad \dot{m}'_{i-1,j} = 0 ; \tag{3-30}$$

$$ND_{i-1,j-1} = \left(\frac{\dot{m}'_{i-1,j}}{\dot{m}_{i-1,j-1}}\right) N_{i-1,j-1} , \qquad \dot{m}'_{i-1,j} > 0 ; \tag{3-31}$$

and

$$NI_{i,j} = N_{i-1,j} + NU_{i-1,j+1} + ND_{i-1,j-1} . \tag{3-32}$$

The space- and cycle-dependent or time-dependent final concentrations of radionuclides $N_{i,j}$ inside the control volumes are calculated by using the governing equation (3-18) and the results from Eq. (3-32).

The radioactivation equations are solved by using the subroutine ACTRA of the computer program RNATPA1 presented in Appendices A and B. Figure 3-7 shows the positions in the control volume in which the variables, calculated by the radioactivation equations, are considered in TAM.

Volumetric Source Equations

Governing equations. The governing volumetric source equations used in TAM are:

a) volumetric radioactive source strength in a control volume:

$$S_{i,j,t_{act}} = \lambda N_{i,j,t_{act}} \tag{3-33}$$

b) production rate of radionuclides in a control volume:

$$\dot{R}_{i,j} = f \rho_{i,j} \sigma \phi_{i,j} \tag{3-34}$$

c) total volumetric radioactive source strength in a station:

$$S_{i,t_{act}} = \frac{\sum_{j=1}^{m1} s_{i,j,t_{act}} A_{i,j}}{\sum_{j=1}^{m1} A_{i,j}} \qquad (3\text{-}35)$$

Numerical solution. Equations (3-33) to (3-35) are used in the numerical solution of the volumetric source equations performed in subroutine ACTRA of the program RNATPA1.

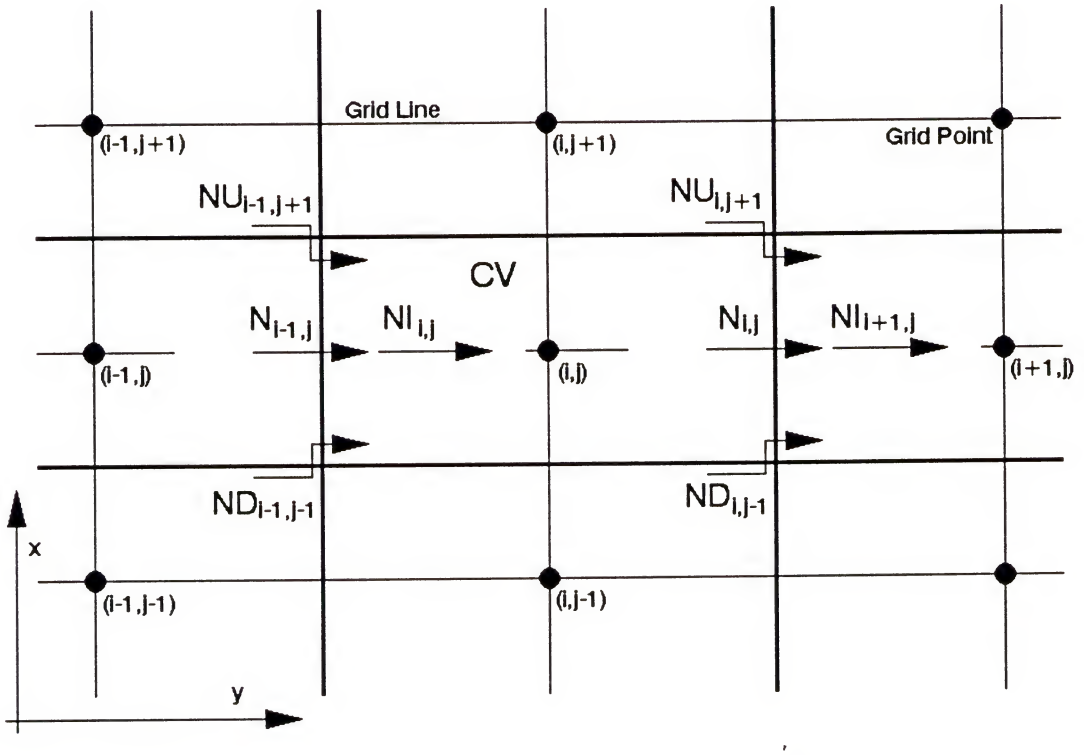


Figure 3-7. Positions in the control volumes (CV) in which the transferred concentrations, the initial concentrations, and the final concentrations of radionuclides, calculated by the radioactivation equations, are considered in TAM.

The Gamma Ray Dose Methodology (GAM)

GAM was developed to calculate the space- and time-dependent gamma ray dose equivalent rate at a point outside a pipe having radionuclides flowing through it.

Definition of the Problem

As explained in the activation and transport methodology, moving radionuclides inside a pipe generate space-dependent volumetric radioactive sources that can be calculated as a function of the number of cycles or the activation time. The geometric dimensions and the volumetric radioactive sources provided by the activation and transport methodology are used in the gamma ray dose methodology to calculate the gamma ray dose equivalent rates, outside the shield of the pipe, from radionuclides moving inside it.

The space-dependent volumetric radioactive sources are integrated over small control volumes to provide the strengths of point radioactive sources at discrete positions inside the pipe. The point-kernel technique [21] is used to calculate the gamma ray dose equivalent rates that these point sources generate at a specific position outside the shield of the pipe. This position will be considered as the position of the detector.

Since the gamma rays from the point radioactive sources cross different layers of materials (fluid, the wall of the pipe, shielding materials, and air) to reach the point of

interest, the methodology considers that a multilayered shield exists between the source and the detector.

The coordinate system, grid points, and control volumes are the same as those used in the activation and transport methodology. However, in the gamma ray dose methodology the index k is added to denote sectors in the angular direction. This means that a control volume is now identified by the indexes i,j, and k. Also, new indexes are used to calculate the buildup factors and the gamma ray dose equivalent rates. These indexes are nlc, npc, and nvsc. The index nlc denotes a particular layer within a multilayered shield, the index npc identifies a photon emitted by a radioactive source, and the index nvsc defines a radioactive source (e.g., argon-41 radioactive source, nitrogen-16 radioactive source, etc.).

Buildup factor for multilayered shield

The appropriate method to calculate the buildup factors for multilayered shields is to solve the Boltzmann transport equation but, for the reasons pointed out in Chapter 2 (i.e., cost, complication, and the time consuming nature of such an elaborate transport method), a simpler method is used.

A comparative study of the method suggested by Chilton et al. [21], Goldstein's Method of an Effective Atomic Number, and Broder's formula [9,20] was carried out to identify the most appropriate technique to be used in this gamma ray dose

methodology. Figures 3-8 and 3-9 show the results of this study for two-layer and three-layer shields.

Two different shielding arrangements were used: water and iron for the two-layer shield; and water, iron, and concrete for the three-layer shield. Goldstein's method and Broder's formula, both suitable for multilayered shields, were used with the method suggested by Chilton et al., suitable only for laminations of two different materials, to calculate the buildup factors for the two-layer shield. Only Goldstein's method and Broder's formula were used for the three-layer shield.

The method of Chilton et al. and Broder's formula take into account the sequence in which the gamma rays cross the layers. To compare the results, the positions of the materials were changed in the two-layer shield.

When the water precedes the iron, all methods present results with errors within the experimental error limits of the buildup data. When the opposite occurs, the results from the method of Chilton et al. are greater than those from Goldstein's method and Broder's formula. The methods for multilayered shields, when applied to a two-layer shield, in which the low-Z material precedes the high-Z material, present results that concur with those provided by the method of Chilton et al., which is specific for such a system.

Figure 3-8 shows the values of the dose buildup factors for a water, iron, and concrete three-layer shield. The

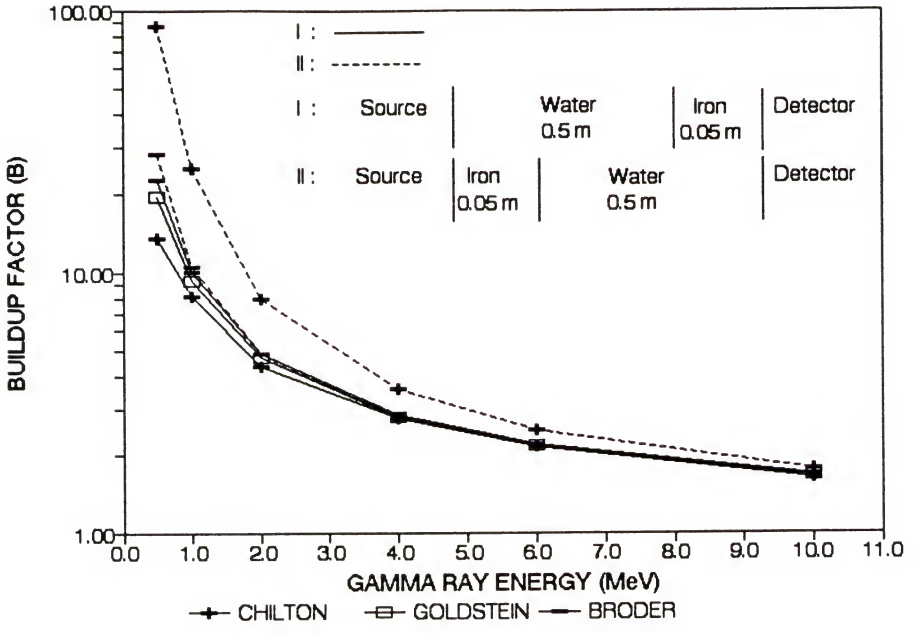


Figure 3-8. Dose buildup factors for a laminated shield consisting of water and iron.

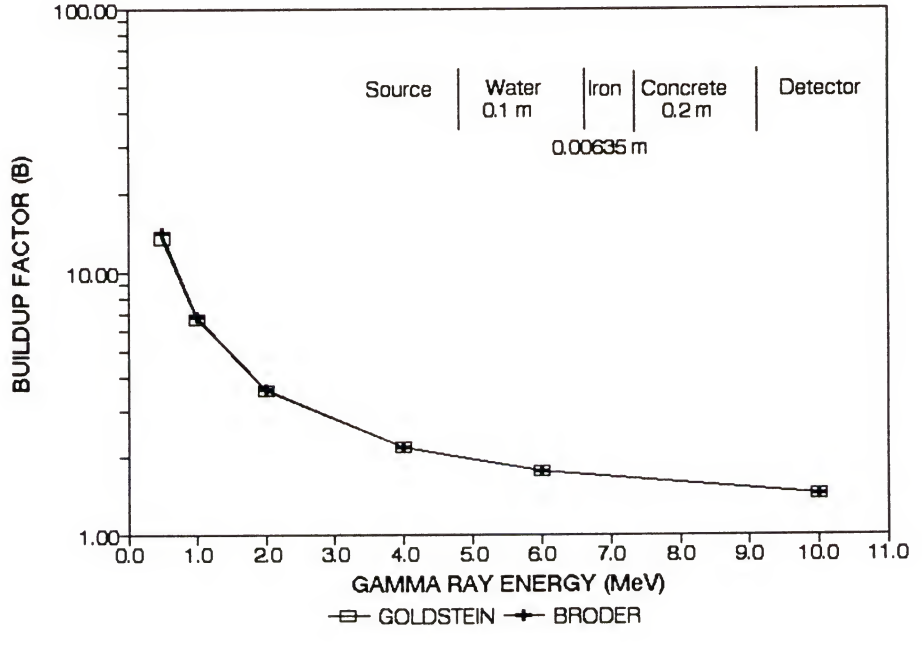


Figure 3-9. Dose buildup factors for a multilayered shield consisting of water, iron, and concrete.

results from Goldstein's method and from Broder's formula are almost the same.

The comparative study shows the adequacy of Goldstein's method and Broder's formula for the gamma ray dose methodology. The fluid, the wall of the pipe, and the shielding materials characterize a multilayered shield. Transport through at least two layers will be present (fluid and the wall of the pipe) and in most of the situations a low-Z material (fluid) will precede a high-Z material (the wall of the pipe). Goldstein's method was chosen and incorporated into the methodology because it allows the user to design interpolation tables for buildup parameters to best suit his or her needs. Also, with Goldstein's method, the user can incorporate these tables into the computer program developed for the methodology or store them in files to be read whenever necessary, reducing the amount of input data.

The governing equations used in the Goldstein's method are discussed below.

The buildup factors are calculated for each control volume, each radionuclide, and each gamma ray. For convenience, when a variable is mentioned, or is explained, the indexes will be dropped.

The first step in Goldstein's Method of an Effective Atomic Number is the calculation of the effective atomic number $\overline{Z}$ for the shield from

$$\overline{Z}_{i,j,k,npc} = \frac{\sum_{nlc=1}^{nl} Z_{nlc}\,\mu_{npc,nls}\,l_{i,j,k,nlc}}{\sum_{nlc=1}^{nl} \mu_{npc,nlc}\,l_{i,j,k,nlc}} \qquad (3\text{-}36)$$

where Z is the effective atomic number of a layer, μ is the linear attenuation coefficient for a gamma ray in the material of a layer, and l is the distance inside the layer. The linear attenuation coefficient for a gamma ray should not be confused with the viscosity of the fluid in TAM. The same symbol was used for both variables because it is traditional and well-known in fluid flow as well as in shielding calculation. The two applications of the symbol will never appear in the same equation.

The effective atomic number $\overline{Z}$ of the multilayered shield and the energy E of the gamma ray are then used to find, from interpolation tables, the parameters $\overline{a}$ and $\overline{b}$ used in Berger's formula for buildup calculation. The buildup factor B for the dose calculation is obtained from

$$R_{i,j,k,npc} = \sum_{nlc=1}^{nl} \mu_{npc,nlc}\,l_{i,j,k,nlc} \qquad (3\text{-}37)$$

and

$$B_{i,j,k,npc} = 1 + \overline{a}\,R_{i,j,k,npc}\,e^{\overline{b}R_{i,j,k,npc}} \qquad (3\text{-}38)$$

where R is the total mean-free-path length of the multilayered shield.

Gamma Ray Dose Equivalent Rate

The gamma ray dose equivalent rate at the position of the detector is computed from each control volume, each point source and each gamma ray, using the point-kernel technique. The governing equations used for this calculation are discussed below.

The point source strength S_0 is given by

$$S_{0_{i,j,k,nvsc}} = 2\pi \frac{x_i A_j}{ns} s_{i,j,nvsc} \qquad (3\text{-}39)$$

where x is the width of the control volume in the x direction, A is the area of the face of the control volume normal to the x direction, $s_{i,j,nvsc}$ is the volumetric radioactive source calculated in the activation and transport methodology, and ns is the number of angular sectors.

In the gamma ray dose methodology, water is used to simulate tissue. This simulation is used because within the range of about 0.1 to 10.0 Mev the mass energy absorption coefficients for a gamma ray in water, compact bone, and striated muscle are almost the same [7, p. 560]. The dose equivalent rate $\dot{d}$ generated at the position of the detector by a gamma ray of a point radioactive source of strength S_0 is calculated from

$$K_{i,j,k,npc} = \frac{B_{i,j,k,npc}}{4\pi L_{i,j,k}^2} e^{-R_{i,j,k,npc}}, \qquad (3\text{-}40)$$

$$\varphi_{i,j,k,nvsc,npc} = K_{i,j,k,npc} S_{0_{i,j,k,nvsc}} Y_{npc} E_{npc} , \qquad (3\text{-}41)$$

$$\dot{d}_{i,j,k,nvsc,npc} = \varphi_{i,j,k,nvsc,npc} \left(\frac{\mu_{en}}{\rho} \right)_{H_2O} , \qquad (3\text{-}42)$$

and

$$\dot{h}_{i,j,k,nvsc,npc} = \dot{d}_{i,j,k,nvsc,npc} . \qquad (3\text{-}43)$$

In Eq. (3-40), K is the point kernel and L is the distance between the point source and the detector. In Eq. (3-41), φ is the energy flux at the detector, Y is the yield of the gamma ray, and E is the energy of the gamma ray. In Eq. (3-42) $\dot{d}$ stands for the absorbed dose rate and $(\mu_{en}/\rho)_{H_2O}$ is the interpolated value of the mass energy absorption coefficient for the gamma ray in the water. In Eq. (3-43), $\dot{h}$ is the dose equivalent rate and has the same value of the absorbed dose rate $\dot{d}$ because the Quality Factor for gamma rays is 1.0. In Eq. (3-42), the mass energy absorption coefficient for gamma ray in water can be replaced by other gamma ray flux-to-dose-rate factors [23,24]. The conversion factors in references 23 and 24 consider the orientation of the dose receptor with respect to the radiation field and permit to solve more specific problems.

Numerical Solution

Equations (3-36) to (3-43) are computed by using the computer program GRDOSER presented in Appendices A and C. In

the numerical solution, the individual contributions at the position of the detector are added and the total gamma ray dose equivalent rate $\dot{H}$ is given by

$$\dot{H} = \sum_{i=ini}^{ifin} \sum_{j=2}^{m2} \sum_{k=1}^{ns} \sum_{nvsc=1}^{nvs} \sum_{npc=1}^{np} \dot{h}_{i,j,k,nvsc,npc} \qquad (3\text{-}44)$$

where *ini* denotes the position in the x direction of the first station within the length of the pipe to be considered, *ifin* denotes the position in the x direction of the last station within the length of the pipe to considered, *nvs* is the number of radioactive volumetric sources, and *np* is the number of photons emitted.

Computer Programs

The numerical calculations required by the methodologies are performed by two computer programs. These computer programs, presented in Appendices A, B, and C are the program Radionuclide Activation and Transport in Pipe, RNATPA1, and the program Gamma Ray Dose Equivalent Rate, GRDOSER. RNATPA1 includes the numerical solutions of TAM while GRDOSER includes those of GAM.

The programs are designed to solve problems of this dissertation within the conditions established at the beginning of this chapter. The program architectures are based on subroutines that can be easily modified or extended to include solutions for all the situations of interest in the generic space- and time-dependent case of mass transport of

radionuclides, their production and decay, and the associated dose rates for fluids flowing through vessels and pipes. The program architectures, and the possibilities they offer to be modified and extended, make RNATPA1 and GRDOSER very flexible frameworks for users.

RNATPA1 has two parts: an invariant part and an adaptation part. The invariant part contains the general calculation schemes needed in TAM and provides solutions for the fluid flow, coupling, radioactivation, and volumetric source equations. The adaptation part provides the problem specification. In this part the user defines the specific details of the problem geometry, fluid properties, flow schemes, radiation fields, activation scenarios, desired outputs, etc.. There is considerable freedom in designing the adaptation part and very complex adaptations are possible.

GRDOSER by itself is an invariant program. Its task is to compute the individual contributions to the dose equivalent rate, at a point outside the pipe, from the space- and time-dependent distribution of gamma ray point sources inside the pipe. The actual details about the geometry and source terms are supplied by coupling files created by RNATPA1. Details related to the shielding are provided in a single input file designed for each problem to be solved. GRDOSER was designed to be used cooperatively with RNATPA1.

CHAPTER 4
RESULTS AND DISCUSSION

Sample Problems

Objectives

The main objectives of the sample problems are:

a) To demonstrate that TAM and GAM can be used to predict the space- and time-dependent behavior of radioactivated fluids flowing through pipes; and

b) To enhance the understanding of the mass transport of radionuclides, their production and decay, and the associated dose rates related to radioactivated fluids flowing through pipes.

The best way to validate the results of the methodologies developed in this dissertation would be by comparing them with experimental results. However, multiple literature searches of unclassified nuclear information indicated that no experimental data related to the space- and time-dependent phenomena addressed in this dissertation have been published. Then, sample problems were selected to verify the calculations performed by TAM and GAM. The sample problems must therefore allow comparisons with analytical expressions, for simple

cases, and reproduce the expected behavior of phenomena that have been studied in other situations.

Analytical expressions are not always sufficiently accurate for calculating the activation of moving fluids inside pipes. Analytical expressions consider batch processes in which time is the only independent variable. The control-volume formulation used in TAM accounts for the space-time dependence of the processes. Comparative studies are carried out, in the sample problems, to compare the results from RNATPA1 with those from analytical expressions. Initially, RNATPA1 is used to calculate a time-dependent problem to compare its results with those from an analytical expression. RNATPA1 is subsequently used to solve a space-dependent problem to illustrate differences from the analytical solution.

It is important to explain, at this point, that in a batch process (normally considered in analytical expressions) the number of cycles is used as the independent variable instead of the time. It is assumed that the time the bulk of the fluid experiences transport, activation and decay, in each cycle, is the same for all cycles. In this situation, the processes can be considered cycle dependent. RNATPA1 also consider cycle-dependent processes, but not as batch processes (see Chapter 3). To simulate batch processes, RNATPA1 utilizes only a single control volume in the y direction. The reader needs to be aware of this difference when comparing the

sample problems. Any time that RNATPA1 is used to simulate an analytical solution (batch process), this condition will be pointed out.

Comparisons with analytical solutions verify that RNATPA1 is written correctly and that the governing equations used appropriately simulate the space- and time-dependent batch processes. To verify that RNATPA1 is able to predict more complex situations, other empirical studies need to be developed as discussed below.

The space- and time-dependent transport, activation and decay processes of radionuclides in fluids flowing through pipes depend upon the pipe, fluid, flow scheme, neutron flux, parent nuclides, and daughter radionuclides. It is beyond the scope of this work to present sample problems involving all possible combinations of these conditions. But, according to the conditions established for this work, the freedom of choice is restricted to fluid, parent nuclides, and daughter radionuclides. To generalize the lessons from the sample problems, the behaviors of the short-lived radionuclides nitrogen-16 and oxygen-19, and long-lived radionuclide argon-41, in fluids as different as air (gas) and water (liquid) are studied.

The sample problems designed to be solved using the computer programs RNATPA1, developed for TAM, and GRDOSER, developed for GAM, are identified as follows:

Sample Problem 1: Activation of Air Inside a Radiation Field.

Sample Problem 2: Activation of Air and Water Inside a Reactor.

Sample Problem 3: Gamma Ray Dose from Radioactivated Air Moving Inside a Pipe.

The study of the activation of air inside a radiation field, in sample problem 1, is initially developed to compare the results provided by RNATPA1 with the results of the analytical solution. This sample problem is also used to perform parametric studies using cycle-dependent and time-dependent activation scenarios.

The study of the activation of air and water inside a reactor, in sample problem 2, is developed to verify the behavior of short-lived and long-lived radionuclides in air or water flowing through pipes that cross different radiation fields. A comparative study on both a qualitative and quantitative basis, is also presented for the induced activity of nitrogen-16 per unit volume of water in each portion of the coolant circuit of the reactor.

The gamma ray dose equivalent rates from radioactivated air moving inside a pipe is studied in sample problem 3. RNATPA1 is used to calculate the space- and time-dependent nitrogen-16 and argon-41 source terms in the radioactivated air moving inside the pipe. GRDOSER is used to calculate the dose rate curves outside the pipe from the radionuclides

moving inside of it. In sample problem 3, the results from GRDOSER are compared with those provided by analytical expressions when the argon-41 volumetric radioactive source distribution in air in the external loop of the pipe is considered constant.

The conclusions drawn from the sample problems cannot be considered valid for all situations. The reader has to understand that the results reflect the limiting conditions established for the sample problems. However, to verify how well the results from TAM and GAM show that these methodologies are able to predict the behavior of radionuclides activated and transported inside pipes, the sample problems presented in this chapter are considered adequate. The results, discussion, physical interpretations of the phenomena and conclusions are presented for each sample problem. The summary of the sample problems are presented at the end of this chapter.

Limitations

In addition to the conditions established for the scope of this dissertation, the sample problems present two more limitations. The first limitation is that the pipes are considered to be straight. This condition does not consider the effects of pipe bends in the space- and time-dependent processes occurring inside the pipe. The second limitation is that no attenuation of the neutron flux is considered in the

fluid. When the fluid is air, this is a very reasonable assumption, but when the fluid is water, the methodology will overestimate the production rate of radionuclides in the control volumes closer to the centerline of the pipe.

Data

Pipe geometries. The pipe geometries used in the sample problems are presented in Fig. 4-1. They are hypothetical pipes and are intended to model the reactor coolant circuits presented in references 8 and 9. The pipes have an internal diameter of 0.10 m. The materials and thicknesses of the walls of the pipes are not specified in sample problems 1 and 2 because the calculations performed in the program RNATPA1 apply only to internal volumes. In the external loop of sample problem 3, iron 0.007 m thick and ordinary concrete 0.20 m thick are used as the wall of the pipe and the shielding layer. GRDOSER requires this information to perform the gamma ray dose calculations.

Data for the Sample Problems. Tables 4-1 to 4-7 contain the Fortran names and the values of the variables needed to solve the fluid flow and the radioactivation equations. The fluids considered in the sample problems are air and water. The parent nuclides and the daughter radionuclides of interest in air and water are presented in Tables 4-4 and 4-5. Since the internal diameters of the pipes are made equal to 0.10 m, the initial velocities of the fluids are defined as a function

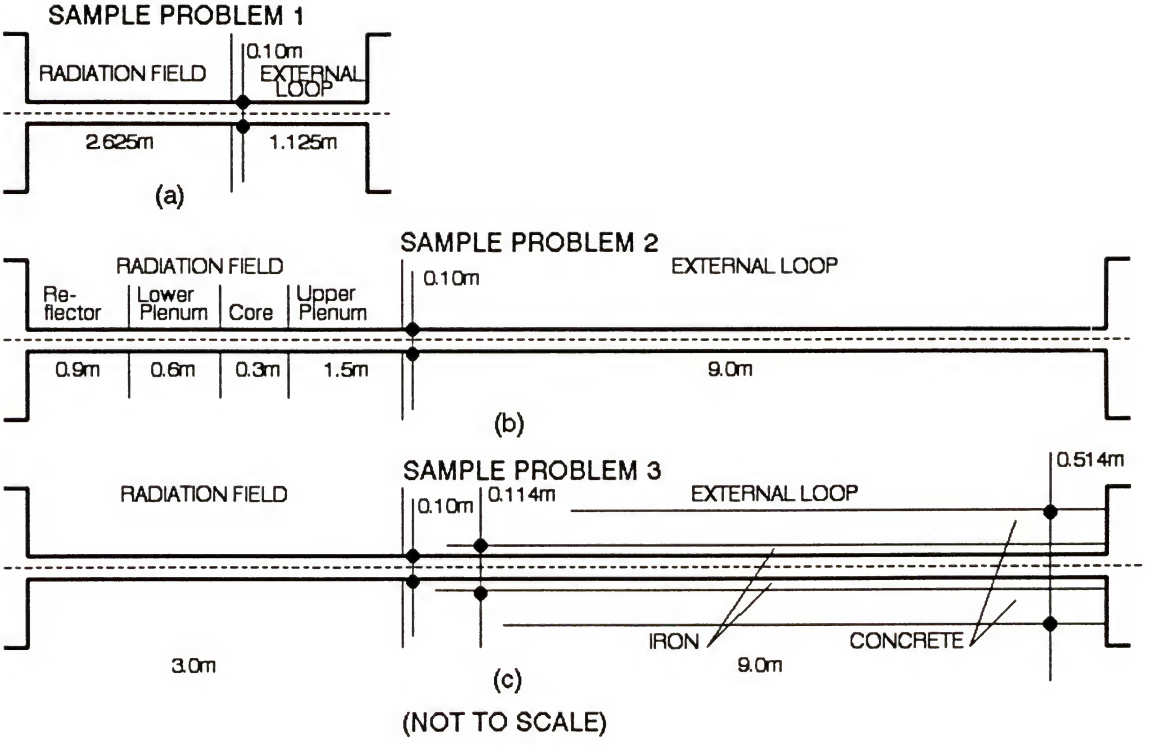


Figure 4-1. Geometric dimensions of the pipe. (a) Sample problem 1; (b) Sample problem 2; (c) Sample problem 3.

of their viscosities to assure laminar flows with Reynolds numbers less than 2000 in all sample problems.

The data used by the program GRDOSER to solve sample problem 3 are not included in the tables described above. The information needed for gamma ray dose calculations from moving nitrogen-16 radionuclides inside the pipe are presented in the GRDOSER.INP input file in Appendix C, which is easily adapted for argon-41 radionuclides.

Table 4-1. Fortran names and units of the physical characteristics of the fluid.

PHYSICAL CHARACTERISTICS	FORTRAN NAME	UNIT
Density of reference	RHOREF	kg/m^3
Temperature of reference	TREF	K
Initial velocity	UIN	m/s
Initial temperature	TIN	K
Viscosity	AMU	Pa s
Constant-pressure specific heat	ACP	J/kg K
Thermal conductivity	AK	W/K m

Table 4-2. Values of the physical characteristics used for air and water.

VARIABLE	AIR	WATER
RHOREF	1.293	999.84
TREF	273.0	273.0
AMU	0.0000186	0.001002
ACP	1007.0	4181.8
AK	0.0262	0.5984

Table 4-3. Fortran names and units of the variables used in the radioactivation process.

VARIABLE	FORTRAN NAME	UNIT
Multiplier factor to calculate the concentration of the parent nuclide	FRA	atom/kg
Neutron activation cross section of the parent nuclide	SIGMA	m^2
Disintegration constant of the daughter radionuclide	ALAMB	s^{-1}
Neutron flux	XPHI	$n/m^{-2}s^{-1}$

Table 4-4. Parent nuclides, fluids, multiplier factors for concentration calculations, neutron activation cross sections and neutron fluxes used in the radioactivation processes.

PARENT NUCLIDE	FLUID	FRA	SIGMA	XPHI
O-16	Air Water	8.703E+24[a] 6.669E+25	1.613E-30[b]	Fast
O-18	Air Water	1.780E+22 1.364E+23	2.100E-32	Thermal
Ar-40	Air	1.926E+23	5.300E-29	Thermal

a. Read as 8.703×10^{24}.
b. Read as 1.613×10^{-30}.

Table 4-5. Parent nuclides, daughter radionuclides, disintegration constants, gamma ray energies and gamma ray yields used in the radioactivation processes and in the gamma ray dose equivalent rate calculations.

PARENT NUCLIDE	DAUGHTER RADIONUCLIDE	ALAMB	GAMMA RAY ENERGY AND YIELD
O-16	N-16	0.0937	2.75 [a](1)[b] 6.13 (69) 7.11 (5)
O-18	O-19	0.0236	0.197 (97) 1.37 (59)
Ar-40	Ar-41	0.00015	1.293 (99)

a. Read as 2.75 MeV.
b. Read as 1 %.

Table 4-6. Initial velocities and temperatures of the fluids and temperatures of the walls of the pipes used in the sample problems.

VARIABLE	AIR	WATER	WALL OF THE PIPE
Sample Problem 1			
UIN	0.15		
TIN	273.0		273.0
Sample Problem 2			
UIN	0.3	0.3	
TIN	300.0	300.0	300.0
Sample Problem 3			
UIN	0.3		
TIN	300.0		300.0

Table 4-7. Neutron radiation fields of the sample problems.

POSITION	THERMAL NEUTRON FLUX	FAST NEUTRON FLUX
Sample Problem 1		
Radiation Field	Flux=A [a]	
	Flux=B [b]	
Sample Problem 2		
Reflector	1.0E+15 [c]	4.0E+14
Lower Plenum	4.0E+14	4.0E+14
Core	1.0E+14	1.0E+15
Upper Plenum	1.0E+14	1.0E+15
Sample Problem 3		
Radiation Field	1.0E+15	1.0E+15

a. $A=B[1+9\cos\pi(0.5-x/2.625)]$, for $0.0 \leq x \leq 1.3125$m,
$A=B[1+9\cos\pi(x/2.625-0.5)]$, for $1.3125 < x \leq 2.625$m.

b. $B=7.5\times10^{14}$ n m^{-2} s^{-1}.

c. Read as 1.0×10^{15} n m^{-2} s^{-1}.

Activation of Air Inside a Radiation Field (Sample Problem 1)

Problem Description

The neutron activation of argon-40 and the transport of argon-41 in air moving through the pipe of Fig. 4-1a are considered in sample problem 1.

Initially a verification is carried out by comparing the numerical solutions of the transport and activation methodology with the solutions provided by an analytical method. Parametric studies of the simulation of the space- and time-dependent transport and activation of radionuclides are also performed with the computer program RNATPA1.

Reference 9 derives an analytical expression and presents a problem to calculate the specific activity of the air at the exit of a radiation field. The analytical expression provided by this reference is

$$\alpha_m = N_{Ar}\sigma\phi\,(1-e^{\lambda t_r})\,[\frac{1-e^{-m(\lambda T)}}{1-e^{-\lambda T}}] \qquad (4\text{-}1)$$

where α_m is the volumetric radioactive source after m cycles, N_{Ar} is the concentration of argon-40 in the air, σ is the thermal neutron activation cross section of the argon-40, ϕ is the constant thermal neutron flux, and λ is the disintegration constant of the argon-41. The average time inside the radiation field is t_r and the average time for one cycle is T.

If the velocity is assumed to be constant and equal to 0.15 m s^{-1} inside the pipe, the air will spend 17.5 s crossing the radiation field and 25.0 s completing one cycle. These times are equal to those used in the proposed problem of reference 9.

The numerical techniques used in RNATPA1 require at least two control volumes in each direction (i.e., the x direction and the y direction) to perform the calculations. The subroutine GRID is designed to simulate the analytical solution. In the x direction different number of control volumes (CVs) are used. In the y direction 2 CVs are used. The CV closest to the wall of the pipe, when made narrow enough, allows one to consider only 1 CV existing in the y direction.

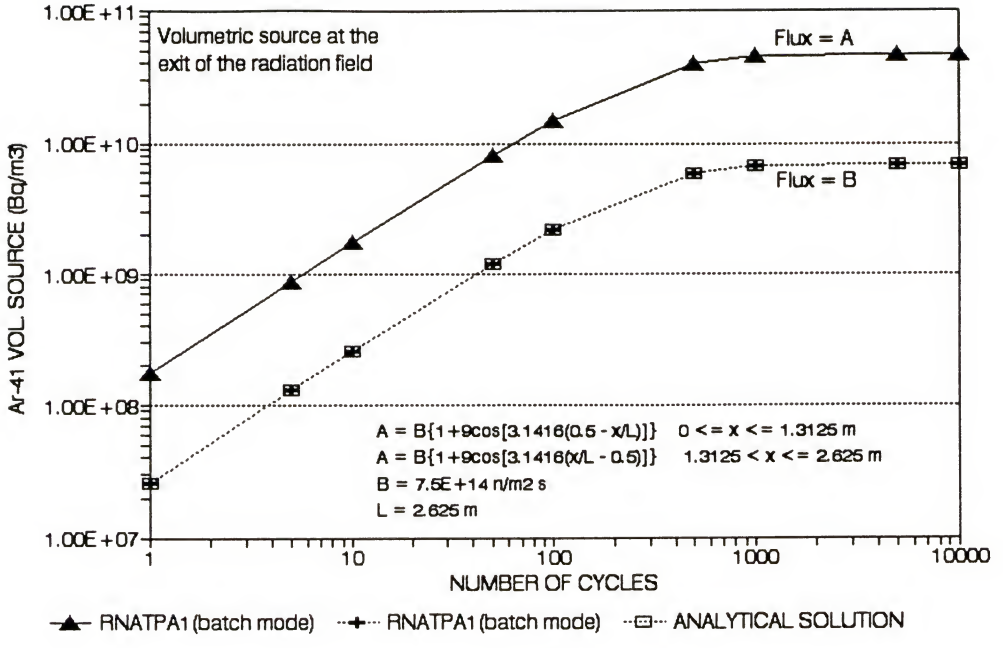
Results and Discussion

Figure 4-2 shows the argon-41 volumetric radioactive sources at the exit of the radiation field calculated by using Eq. (4-1) and RNATPA1, and the argon-41 volumetric radioactive sources along the pipe calculated by using RNATPA1.

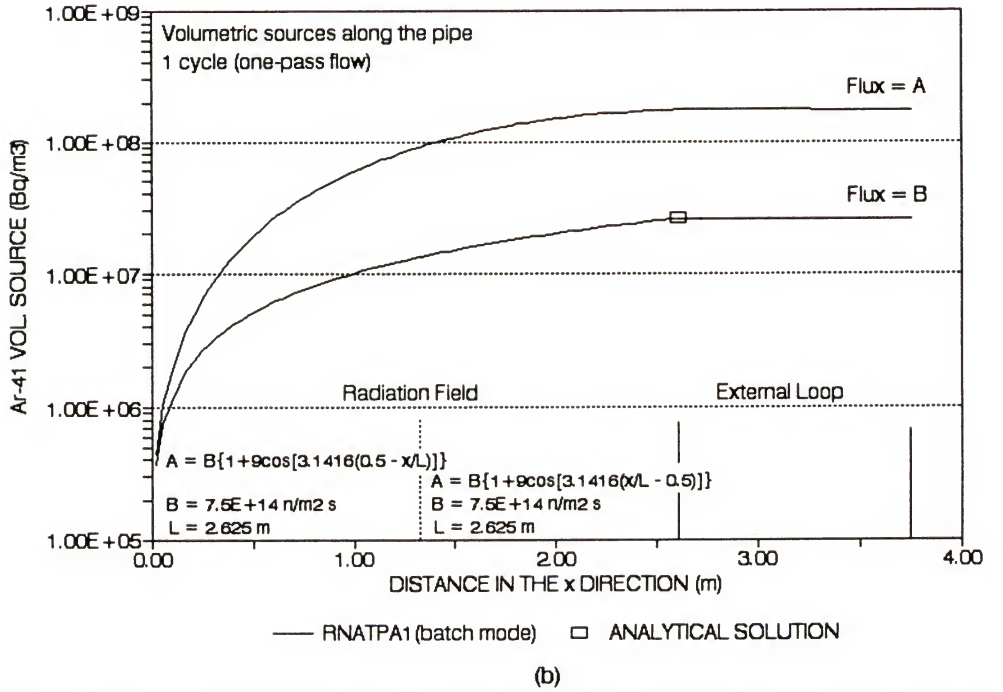
Figure 4-2a shows the volumetric radioactive sources at the exit of the radiation field calculated for different cycles. For a constant neutron flux, the results from RNATPA1 are identical to those obtained from the analytical expression. When spatial dependence is included in the neutron flux, the results from RNATPA1 are also shown in Fig.

4-2a. Equation (4-1) is not used to reproduce the same calculation because it cannot consider the spatial dependence of the neutron flux, a critical limitation of the analytical expression. The results provided by RNATPA1 for the space-dependent neutron flux are larger than those provided for the constant neutron flux. This is expected because in each CV the space-dependent neutron flux is larger than the constant neutron flux.

Figure 4-2b shows the argon-41 volumetric radioactive sources along the pipe, at the end of the first cycle, calculated by using Eq. (4-1) and RNATPA1. As seen in Fig. 4-2b, for a constant neutron flux the analytical expression calculates the volumetric radioactive source only at the end of the radiation field (a single cycle-dependent result at a specific location). RNATPA1, in batch mode, reproduces the value for the volumetric radioactive source calculated by the analytical expression at the end of the radiation field. Moreover, RNATPA1 is able to calculate the volumetric radioactive sources in all positions along the pipe, a task impossible for the analytical expression. When the spatial dependence is included in the neutron flux, the results are also shown in Fig. 4-2b. The results provided by RNATPA1 for the space-dependent neutron flux are larger than those provided for the constant neutron flux for the same reasons explained in the discussion of Fig. 4-2a above.



(a)



(b)

Figure 4-2. Comparison between analytical (Eq. 4-1) and numerical (RNATPA1) solutions for argon-41 volumetric radioactive sources (Sample Problem 1); (a) At the exit of the radiation field; (b) Along the x direction (longitudinal direction of the pipe).

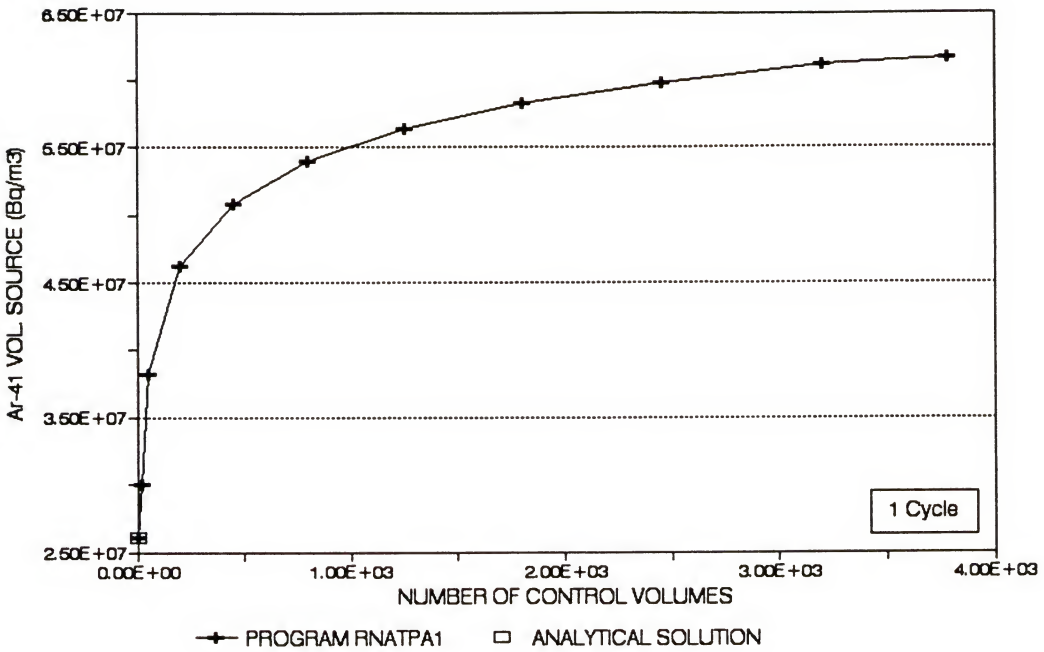


Figure 4-3. Comparison between analytical (Eq. 4-1) and numerical (RNATPA1) solutions for argon-41 volumetric radioactive sources at the exit of the radiation field (Sample Problem 1).

Another difference between the analytical solution and the numerical solution for 1 cycle, constant neutron flux and different numbers of control volumes (NCV) is presented in Fig. 4-3. The argon-41 volumetric radioactive source at the exit of the radiation field calculated by the analytical expression is equal to 2.60×10^{7} Bq m^{-3}. RNATPA1 is used to calculate the argon-41 volumetric radioactive source at the same position using different numbers of CVs in the x direction (NCVX) and in the y direction (NCVY). The ratio NCVX/NCVY is kept equal to 2. The maximum NCV that RNATPA1

can use in a 80486DX IBM-compatible PC with 4 MB of RAM memory is 3780. At this limit, the volumetric source at the exit of the radiation field calculated by the RNATPA1 is equal to 6.17×10^{7} Bq m^{-3}, 2.37 times the result obtained from the analytical solution. It can be seen that when the NCV increases, the volumetric source stabilizes at a value closer to 6.25×10^{7} Bq m^{-3}.

For a developing flow, the fact that velocity profiles are not constant results in different dwell times for air in the various CVs. The activation of argon-40 nuclides and the transport of argon-41 radionuclides are not constant in space and time along the length of the pipe. While analytical expressions cannot be used to solve this problem, the activation and transport methodology and the program RNATPA1, through the coupling and radioactivation equations, are able to solve it. The analytical solution, effectively limited to 1 CV in the y direction, can be considered as a particular case of the activation and transport methodology.

Figures 4-4 and 4-5 exhibit the results of the transport of radionuclides calculated by RNATPA1 in the station at the end of the radiation field. To perform the calculation, 90 CVs are used in the x direction and 42 in the y direction.

The length of the pipe in sample problem 1 does not allow the complete development of the flow. Inside the CVs the fluid still has a small velocity toward the centerline in the y direction.

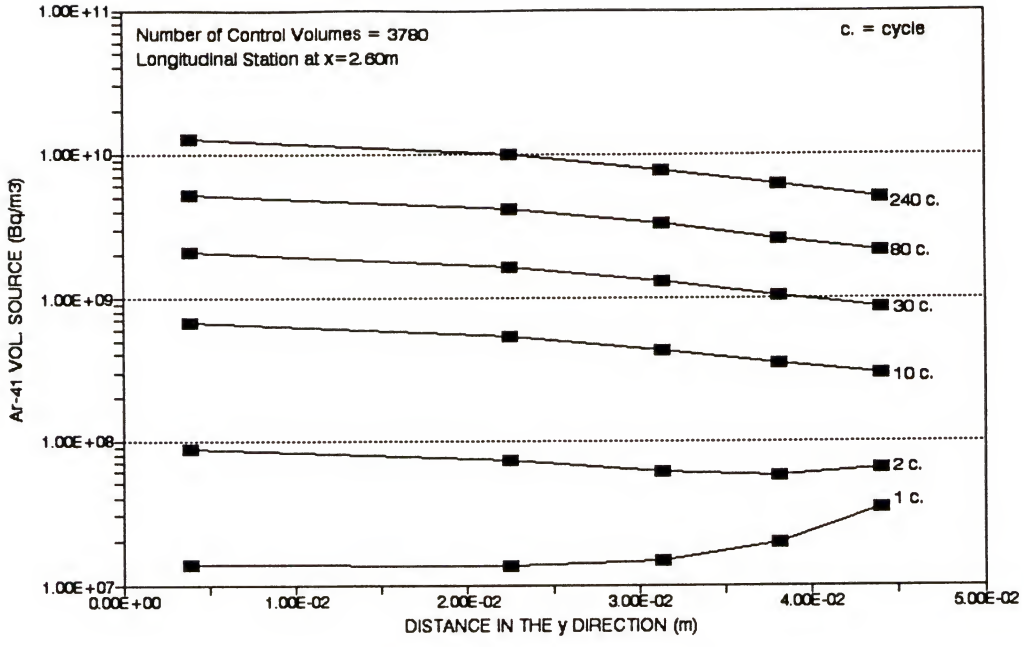


Figure 4-4. Space- and cycle-dependent argon-41 volumetric radioactive sources at the exit of the radiation field (Sample Problem 1).

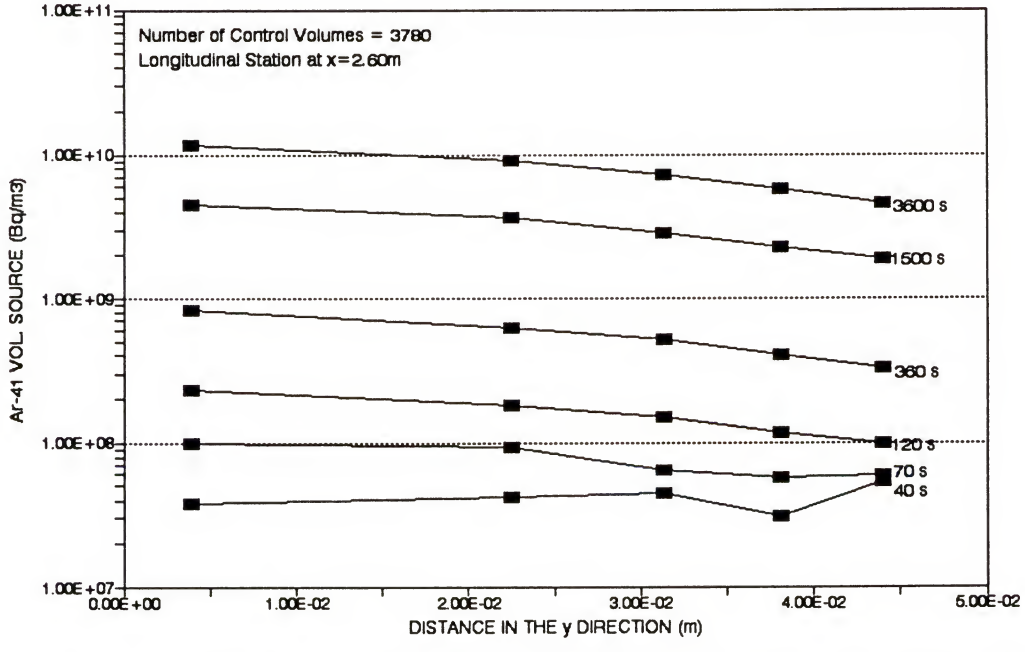


Figure 4-5. Space- and time-dependent argon-41 volumetric radioactive sources at the exit of the radiation field (Sample Problem 1).

The largest time that the argon-41 spends inside the pipe after activation is much smaller than its half-life. Consequently, no significant decay is expected.

Since the flow is not completely laminar inside the pipe, the fluid mass flow rates transferred into or out of the CVs are responsible for the transport and increase in the concentration of radionuclides in the rows of CVs closer to the centerline.

In the cycle-dependent activation scenario, the concentration of radionuclides in a CV is updated at each cycle. The methodology considers each new cycle as a one-pass flow. The initial concentration of radionuclides in the fluid, in a new cycle, is made equal to the average concentration at the exit of the pipe in the previous cycle (i.e., the fluid is mixed before recirculating). For each cycle the concentration of radionuclides inside each CV must increase because of the radioactivation process and the transport of radionuclides produced in the current and previous cycles. The magnitude of the rate of growth of argon-41 increases from the wall to the centerline of the pipe. The rates of growth of the radionuclides are greater in the CVs close to the centerline in each cycle. This explains the changes observed in the curves for argon-41 volumetric radioactive sources, presented in Fig. 4-4, when the number of cycles increases.

In the time-dependent activation scenario, the concentration of radionuclides in a CV is updated according to the activation time. For the same activation time, CVs at the same station may have their concentrations updated. The time controller variable $t1_{i,j}$ (See Fig. 3-6) controls the updating process. Since the recirculation of the fluid occurs, continuously, at each time step, successive waves of radionuclides being transported exist inside the pipe at the same time. It is possible that for a given station, most of the successive waves of radionuclides have already reached CVs close to the centerline while none have reached CVs close to the wall of the pipe. In a station, the first CV that has its concentration changed is the one closest to the centerline and the last is the one closest to the wall. This physical behavior of the transport of radionuclides in recirculating fluids explains the shape of the curve for argon-41 volumetric radioactive sources, presented in Fig. 4-5, when the activation time is 40 s. The growth rates of argon-41 in the CVs closer to the centerline are greater than those in the CVs closer to the wall of the pipe. This explains the changes observed in the curves for argon-41 volumetric radioactive sources, presented in Fig. 4-5, when the activation time increases.

Figures 4-6 and 4-7 present the space- and cycle-dependent and the space- and time-dependent argon-41 volumetric radioactive sources calculated at the exit of the

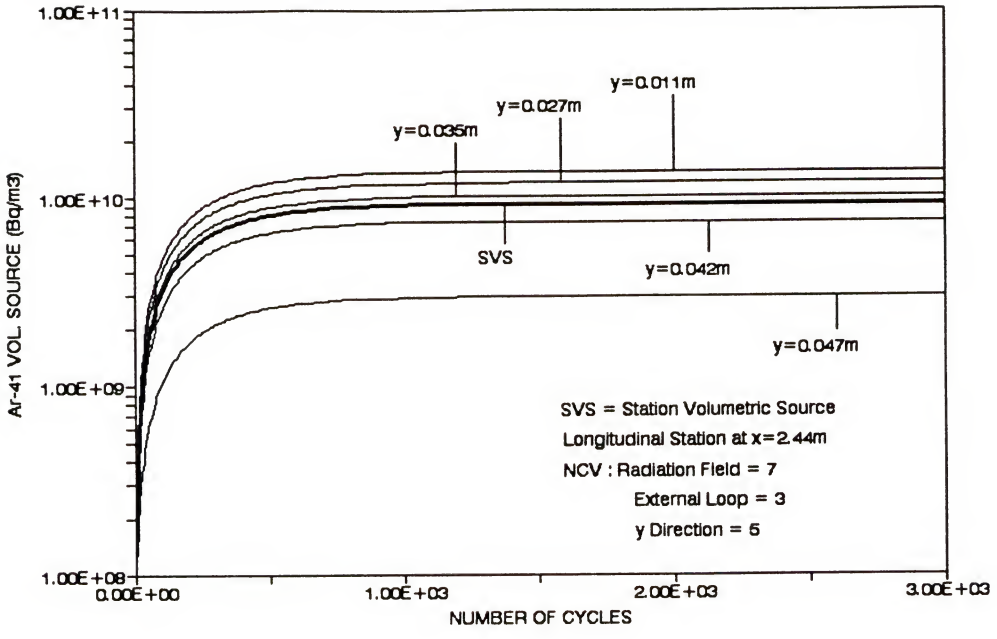


Figure 4-6. Space- and cycle-dependent argon-41 volumetric radioactive sources at the exit of the radiation field (Sample Problem 1).

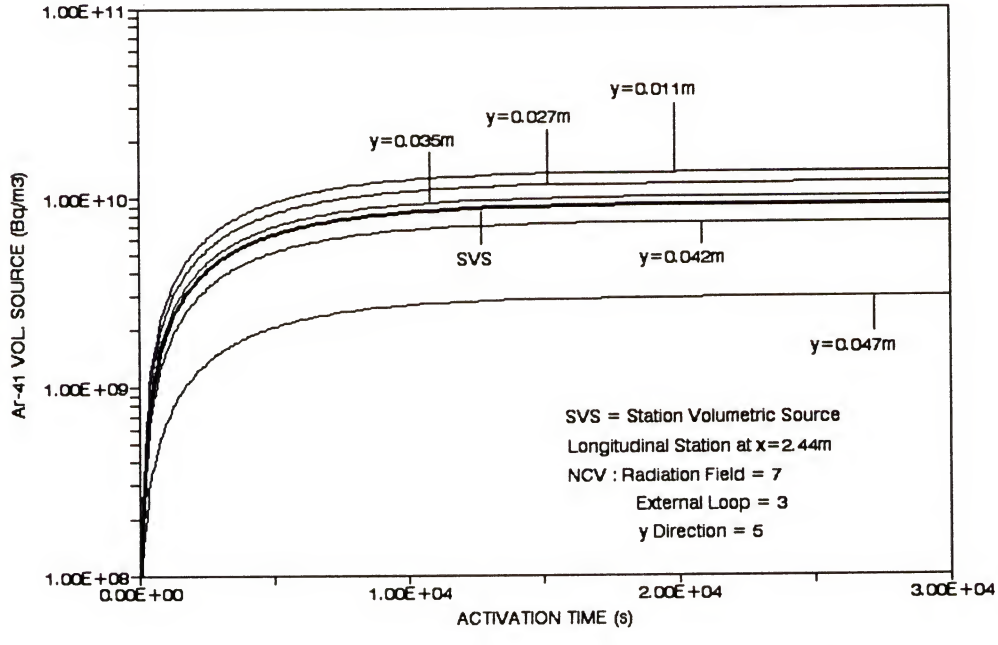


Figure 4-7. Space- and time-dependent argon-41 volumetric radioactive sources at the exit of the radiation field (Sample Problem 1).

radiation field. The station volumetric source (SVS) is the average value of the volumetric sources in the station.

In Figs. 4-6 and 4-7, the concentration of argon-41 in the CV closest to the centerline, y=0.011m, is greater than that in the CV closest to the wall of the pipe, y=0.047m. The accumulated radionuclides decrease in number from the centerline to the wall of the pipe. This behavior is explained in the discussion of Figs. 4-3 and 4-4. The increase in the concentration of radionuclides stops after 1500 cycles and 25000 s. The constant concentrations after these marks indicate that the rate of production and the rate of decay of argon-41 are equal (i. e., the equilibrium is reached).

The comparisons between the results of the numerical method and the analytical expression, illustrated by Fig. 4-2, and the convergence observed in Fig. 4-3, when the NCV are increased, constitute good evidence that the transport and activation methodology and the computer program RNATPA1 are able to simulate the activation and transport of radionuclides inside pipes.

The results of the parametric studies for the two activation scenarios presented in Figs. 4-4 to 4-7 reproduce the expected behavior of argon-41 transported inside the pipe.

Activation of Air and Water Inside a Reactor (Sample Problem 2)

Problem Description

Sample problem 2 is designed to illustrate the calculation of the activity induced in a fluid as it crosses different radiation fields (e.g., reflector, lower plenum, core, and upper plenum) in a nuclear reactor. The series flow scheme presented in references 8 and 10 to calculate the activity induced in water, used as the reactor coolant, is chosen as a model. The pipe shown in Fig. 4-1b simulates the passage of air or water through a cooling circuit.

Rockwell [8, p. 104] derives an analytical expression to calculate the induced activity of nitrogen-16 per unit volume of water in each portion of a coolant circuit. Average times are considered per unit volume of water in the various parts of the system. The analytical expression does not consider the geometry of the pipe. The curve for the typical variation of the nitrogen-16 activity at equilibrium, as the coolant passes through the reactor, is presented on a qualitative basis by the author.

The program RNATPA1 is used to calculate the induced activity in air and in water. Fast and thermal neutron activation are considered. The radionuclides of interest are nitrogen-16, oxygen-19 and argon-41.

Results and Discussion

Figures 4-8 to 4-13 show the results for air. Figures 4-14 to 4-17 show the results for water.

In Figs. 4-8 to 4-10, 4-14 and 4-15 the smallest number of CVs is 41 and the greatest is 2624. The curves for NCV=328 and NCV=2624 are indicated in Figs. 4-11, 4-12, 4-13, 4-16 and 4-17. One CV is used in the y direction for NCV=41 and NCV=328. Eight CVs are used in the same direction to obtain NCV=2624. The results for NCV=41 and NCV=328 correspond to the simulation of the analytical solution. The number of CVs are increased only to show the difference between the analytical and numerical solutions. A demonstration of the convergence of the results, like those in Fig. 4-3, are not intended.

The explanations for the results presented in Fig. 4-3 of sample problem 1 also apply to the results for nitrogen-16, oxygen-19 and argon-41 volumetric radioactive sources in air, and for nitrogen-16 and oxygen-19 volumetric radioactive sources in water, presented in Figs. 4-8 to 4-10, 4-14 and 4-15.

The growth and decay of the radionuclides depend upon the reaction rate and disintegration constant. For a constant reaction rate, radionuclides with the greatest disintegration constant (i.e., with the shortest half-life) have the most rapid growth. For identical elapsed times from the end of activation, radionuclides with the greatest disintegration

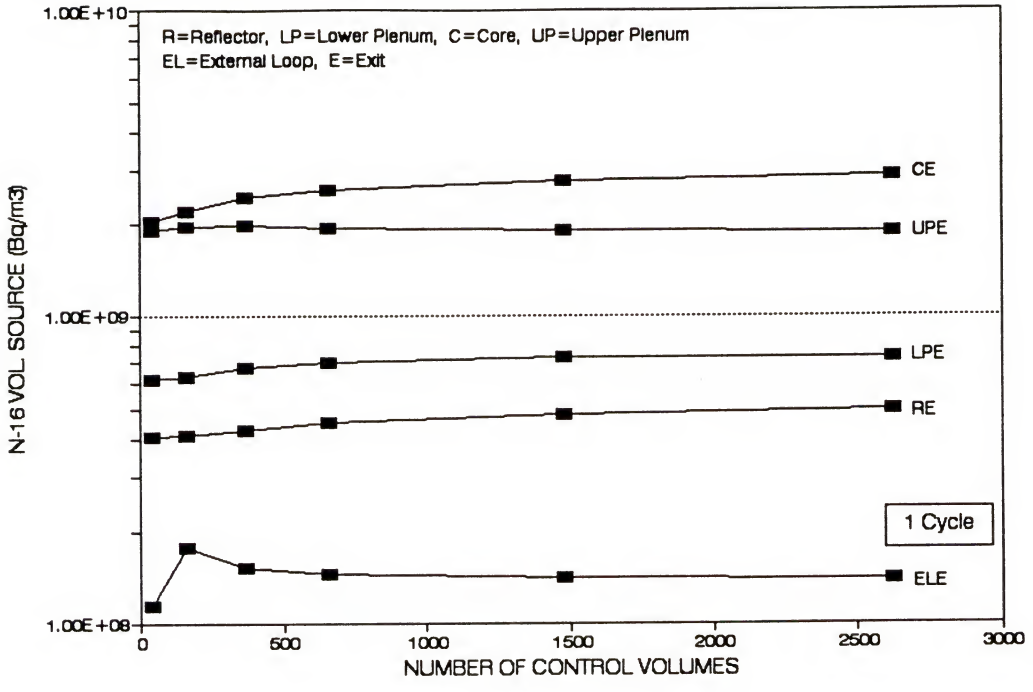


Figure 4-8. Nitrogen-16 volumetric radioactive sources in air at various positions in the pipe (Sample Problem 2).

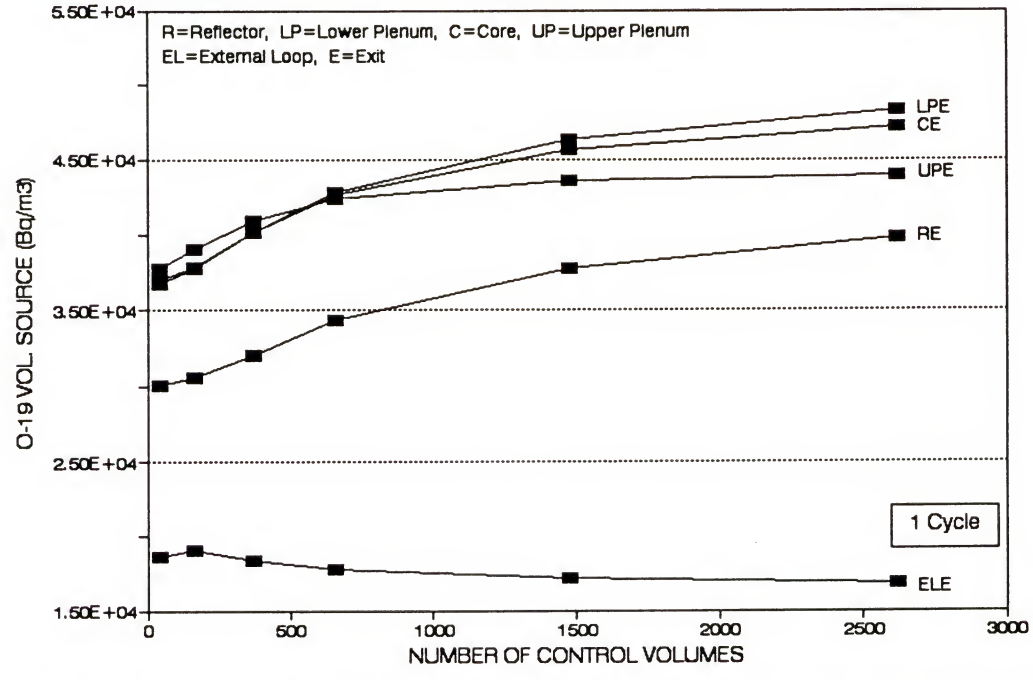


Figure 4-9. Oxygen-19 volumetric radioactive sources in air at various positions in the pipe (Sample Problem 2).

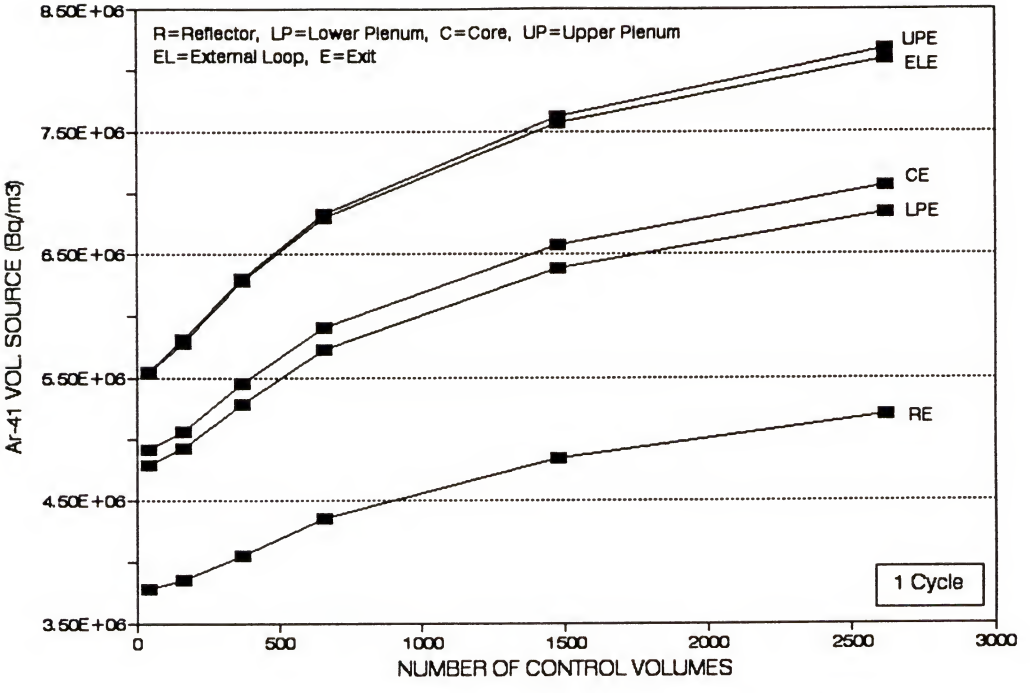


Figure 4-10. Argon-41 volumetric radioactive sources in air at various positions in the pipe (Sample Problem 2).

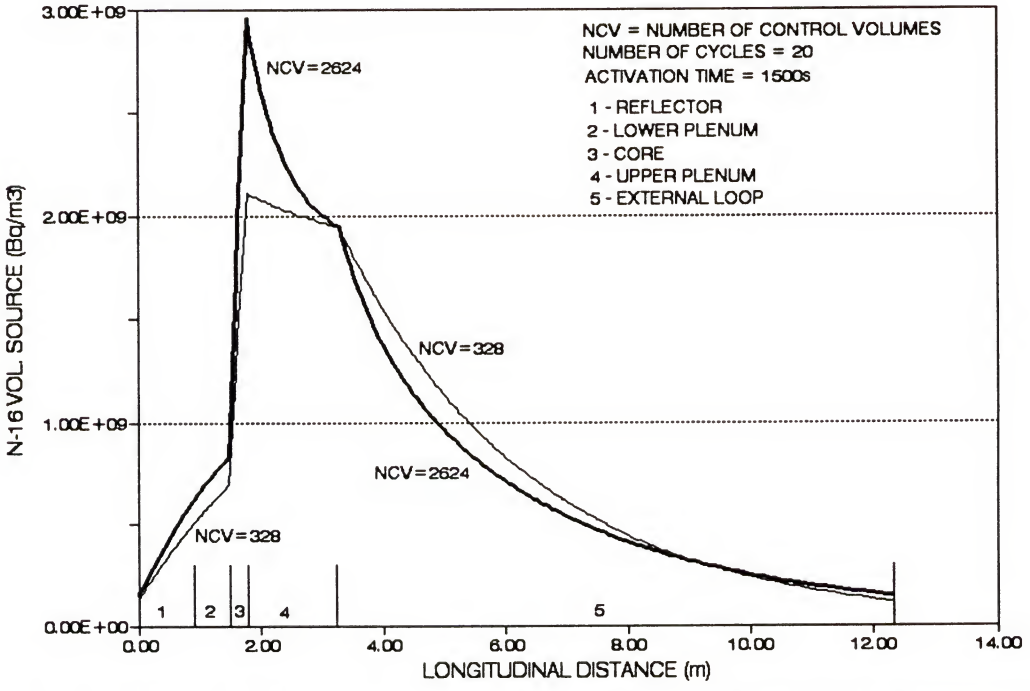


Figure 4-11. Nitrogen-16 volumetric radioactive sources in air along the pipe (Sample Problem 2).

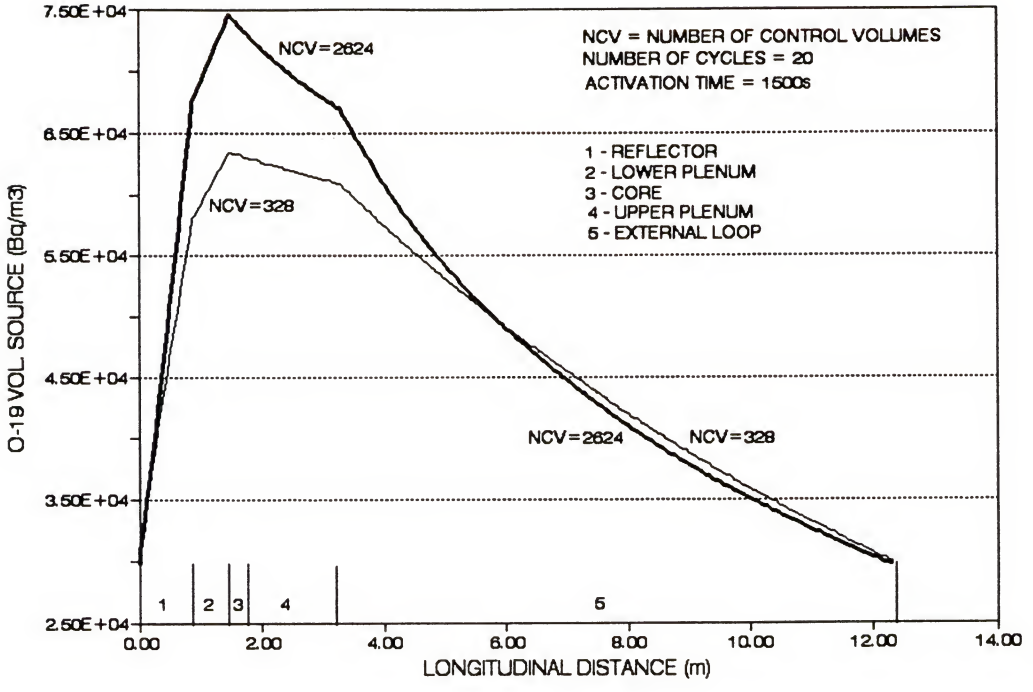


Figure 4-12. Oxygen-19 volumetric radioactive sources in air along the pipe (Sample Problem 2).

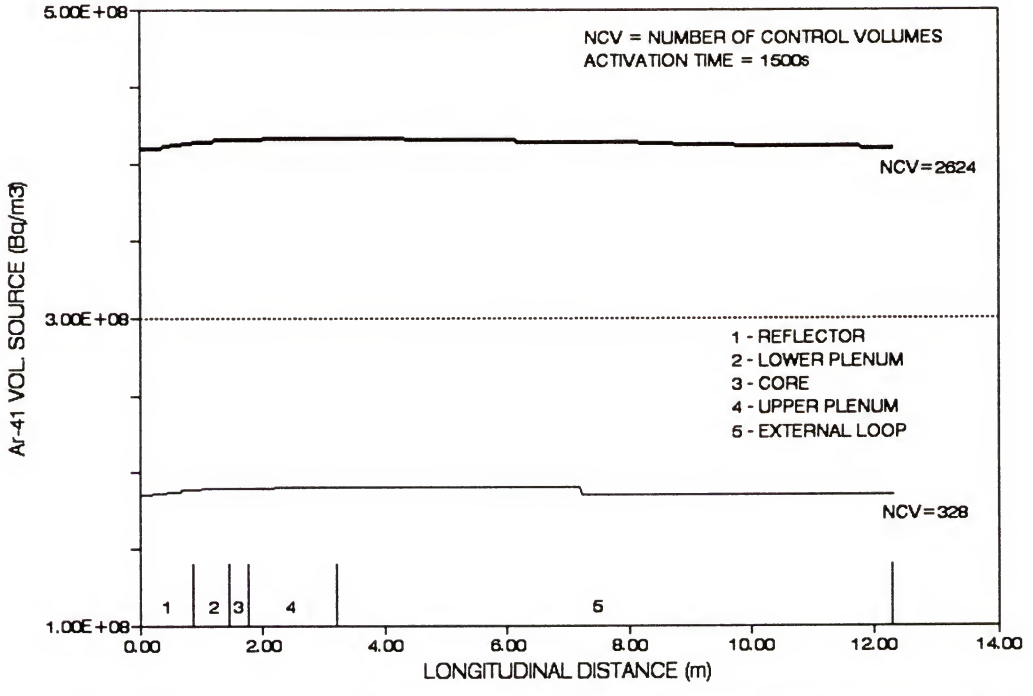


Figure 4-13. Argon-41 volumetric radioactive sources in air along the pipe (Sample Problem 2).

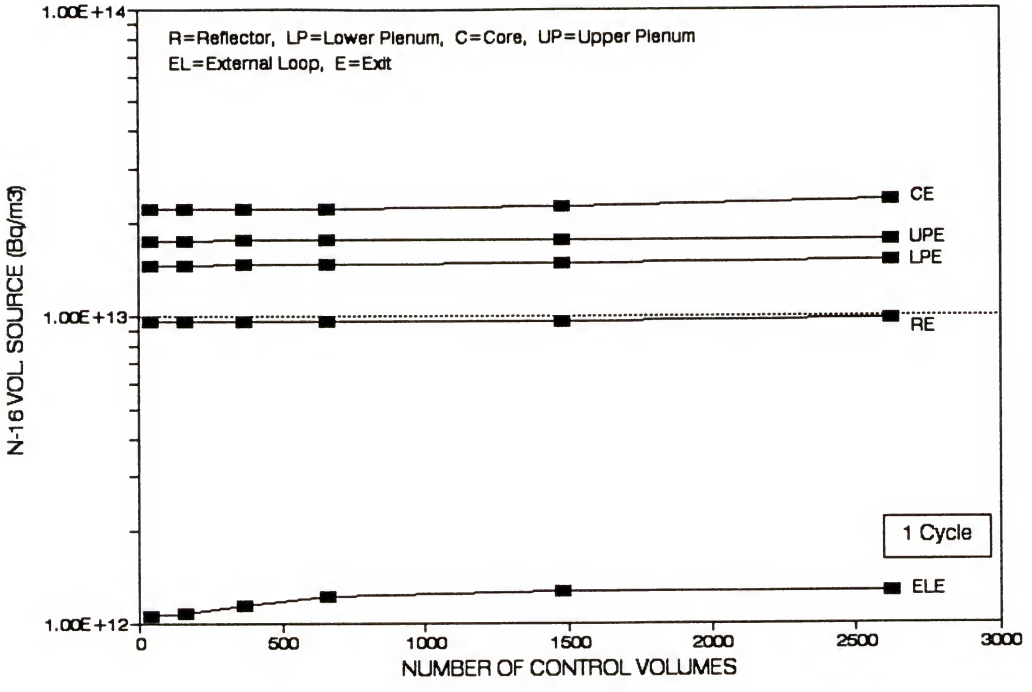


Figure 4-14. Nitrogen-16 volumetric radioactive sources in water at various positions in the pipe (Sample Problem 2).

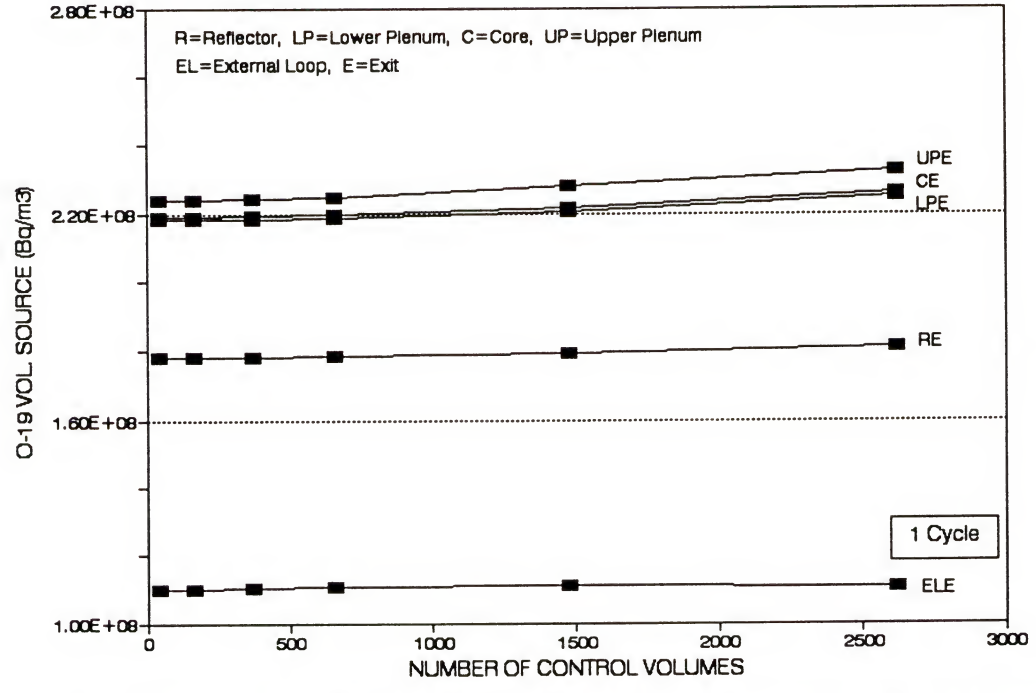


Figure 4-15. Oxygen-19 volumetric radioactive sources in water at various positions in the pipe (Sample Problem 2).

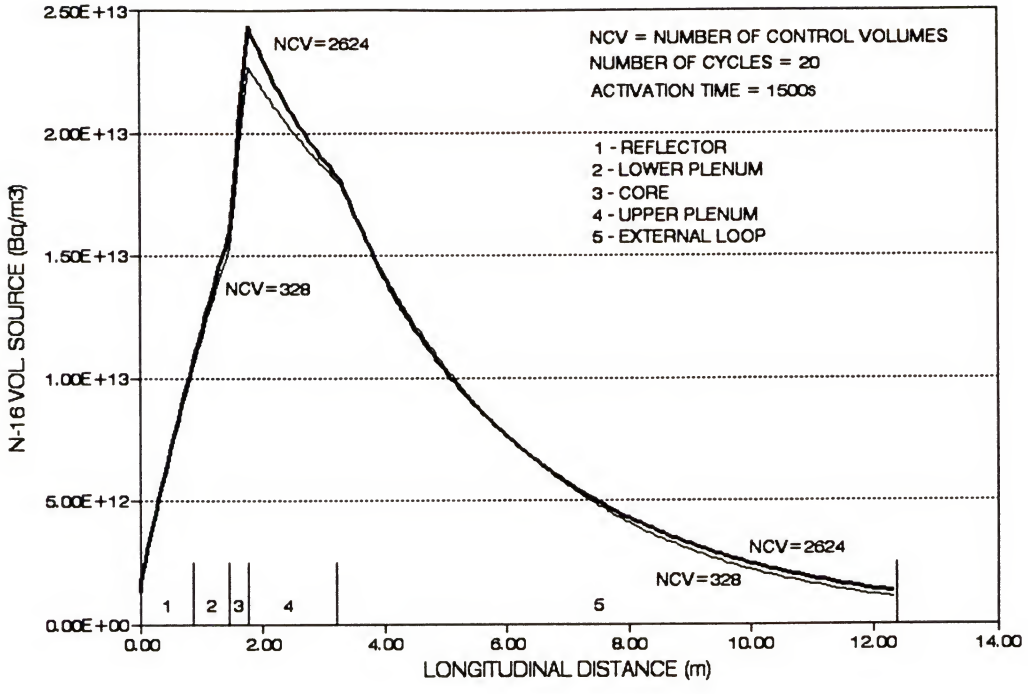


Figure 4-16. Nitrogen-16 volumetric radioactive sources in water along the pipe (Sample Problem 2).

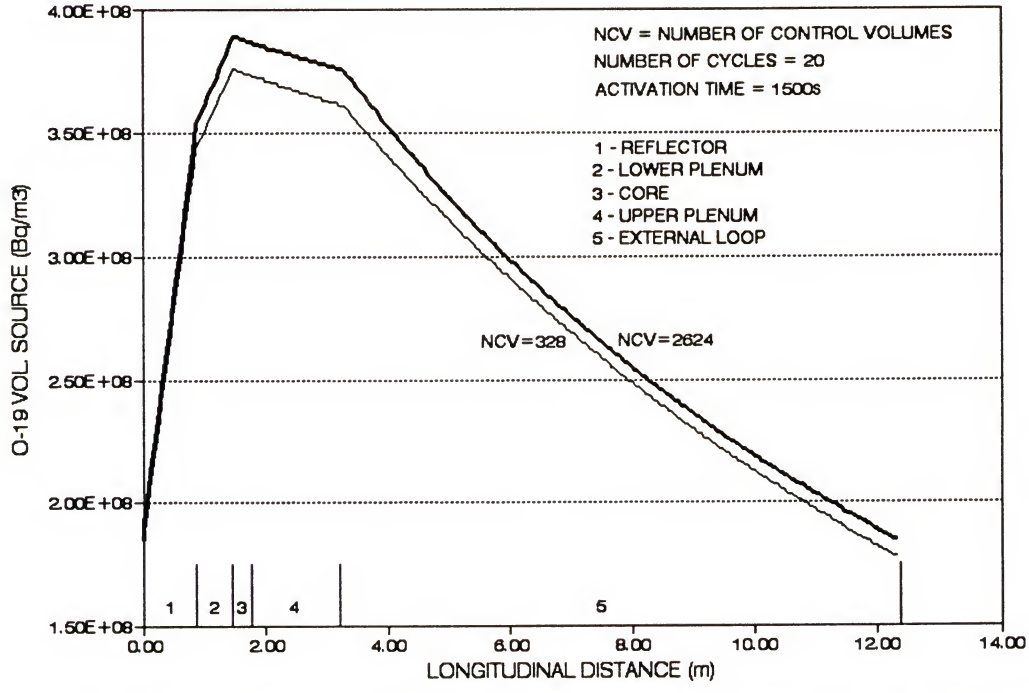


Figure 4-17. Oxygen-19 volumetric radioactive sources in water along the pipe (Sample Problem 2).

constant exhibit the most rapid decay. When equilibrium is reached for a recirculating fluid, the concentrations of radionuclides at the entrance and exit of the pipe are equal. However, inside the radiation field and external loop, the rate of growth and the rate of decay change according to the disintegration constant. The growth and decay are pronounced for short-lived radionuclides and slowly varying for long-lived radionuclides.

Figures 4-11 to 4-13 present the nitrogen-16, oxygen-19 and argon-41 volumetric radioactive sources in air moving through the pipe. The results for 20 cycles, or 1500 s, of activation show that equilibrium has been reached for nitrogen-16 and oxygen-19. The same occurs for argon-41 after 1500 s of activation. Then, the processes explained above are predicted to govern the concentrations of these radionuclides inside the pipe.

Nitrogen-16 has the greatest disintegration constant and argon-41 the smallest. As can be seen from Figs. 4-11 and 4-13, the rate of growth of nitrogen-16 inside the radiation field is greater than that of argon-41. Inside the external loop, the rate of decay of nitrogen-16 is greater than that of argon-41.

For a short-lived radionuclide like nitrogen-16 or oxygen-19, activation and decay are the dominant processes defining the distribution of the volumetric radioactive sources in the CVs. It can be considered that transport plays

a minor role in this distribution. Such an effect can be observed by comparing Figs. 4-8 and 4-11, and Figs. 4-9 and 4-12. There is almost no difference between the nitrogen-16 volumetric radioactive source magnitudes after 1 cycle (Fig. 4-8) and 20 cycles (Fig. 4-11), which means that before equilibrium has been reached the quantity of radionuclides formed in a cycle is practically equal to the quantity that experiences decay in the same cycle. No increase in the concentration of nitrogen-16 radionuclides can be observed. There is a slight difference between the oxygen-19 volumetric radioactive source magnitudes after 1 cycle (Fig. 4-9) and 20 cycles (Fig.4-12), which means that before equilibrium has been reached the quantity of radionuclides formed in a cycle is a little greater than the quantity that experiences decay in the same cycle. A small increase in the concentration of oxygen-16 radionuclides can be observed.

For a long-lived radionuclide like argon-41, activation and transport are the dominant processes defining the distribution of volumetric radioactive sources. Decay has a minor role in the distribution. This effect can be observed when Figs. 4-10 and 4-13 are compared. There is a great difference between the argon-41 volumetric radioactive source magnitudes after 1 cycle (Fig. 4-10) and after equilibrium has been reached (Fig. 4-13). This means that before equilibrium has been reached the quantity of radionuclides formed in a cycle is greater than the quantity that experiences decay in

the same cycle. A large increase in the concentration of argon-41 radionuclides can be observed.

Figures 4-16 and 4-17 show the nitrogen-16 and oxygen-19 volumetric radioactive sources in the water flowing through the pipe. Due to their similarities, the explanations provided for Figs. 4-11 to 4-13 also apply to Figs. 4-16 and 4-17. The results for 20 cycles, or 1500 s, of activation show that equilibrium has been reached for nitrogen-16 and oxygen-19 radionuclides. No increase in the concentration of nitrogen-16 and a small increase in the concentration of oxygen-19 can be observed.

Figure 4-16 quantitatively reproduces the induced activity of nitrogen-16 per unit volume of water in each portion of the coolant circuit that is presented, on a qualitative basis, by Rockwell in reference 8.

The results obtained in sample problem 2 demonstrate the ability of the transport and activation methodology to simulate the physical behavior of both short-lived and long-lived radionuclides activated and transported inside pipes. These results demonstrate the consistency of the methodology and indicate that its solutions provide valuable insight to the behavior of the activation and the transport of different radionuclides for different fluids flowing through pipes.

Gamma Ray Dose from Radioactivated Air Moving Inside a Pipe (Sample Problem 3)

Problem Description

The neutron activation of argon-40 and oxygen-16 in air moving through the pipe of Fig. 4-1c is considered first in sample problem 3. Next, the gamma ray dose equivalent rates generated outside the external loop of the pipe by argon-41 and nitrogen-16 radionuclides in air moving inside of it are considered. The geometry chosen is based on sample problem 2 and the reader can observe the similarities between the Figs. 4-1b and 4-1c.

Sample problem 3 shows how the transport and activation methodology and the gamma ray dose methodology are used together. The transport and activation methodology is used to calculate the space- and time-dependent distributions of the argon-41 and nitrogen-16 volumetric radioactive sources in the recirculating air flowing through the pipe. The gamma ray dose methodology is used to calculate the gamma ray dose equivalent rates generated by these volumetric radioactive sources outside the pipe in the external loop.

Results and Discussion

Transport and activation methodology. The program RNATPA1 is used to calculate the distributions of the argon-41 and nitrogen-16 radioactive volumetric sources along the pipe. The pipe is divided in 120 CVs in the x direction (30 CVs

inside the radiation field and 90 CVs inside the external loop) and 12 CVs in the y direction. The calculations are carried out for an activation time equal to 3600 s.

The results for the rows of CVs surrounding the grid lines y=0.007m, y=0.040m and y=0.049m are presented in Fig. 4-18. The CVs at y=0.047m are closer to the wall and the CVs at y=0.007m are closer to the centerline of the pipe. The results for other rows lie between curves 1 and 2 for both radionuclides. They are not displayed in order to make the figure easy to view and understand.

After 3600 s of activation, the distribution of volumetric radioactive sources along the pipe have reached equilibrium. The equilibrium conditions described in the discussion of sample problem 2 can be seen for both radionuclides in Fig. 4-18.

Activation and decay are the dominant processes in the nitrogen-16 volumetric radioactive source distributions along the pipe. Decays are mainly observed in the rows of CVs inside the external loop. The decay is more prominent at y=0.049m because at this position the radionuclides spend the longest time crossing the pipe and will certainly decay before leaving it.

Activation and transport are the dominant processes in the argon-41 volumetric radioactive source distributions along the pipe. The transport of radionuclides can be observed inside the radiation field as well as inside the external

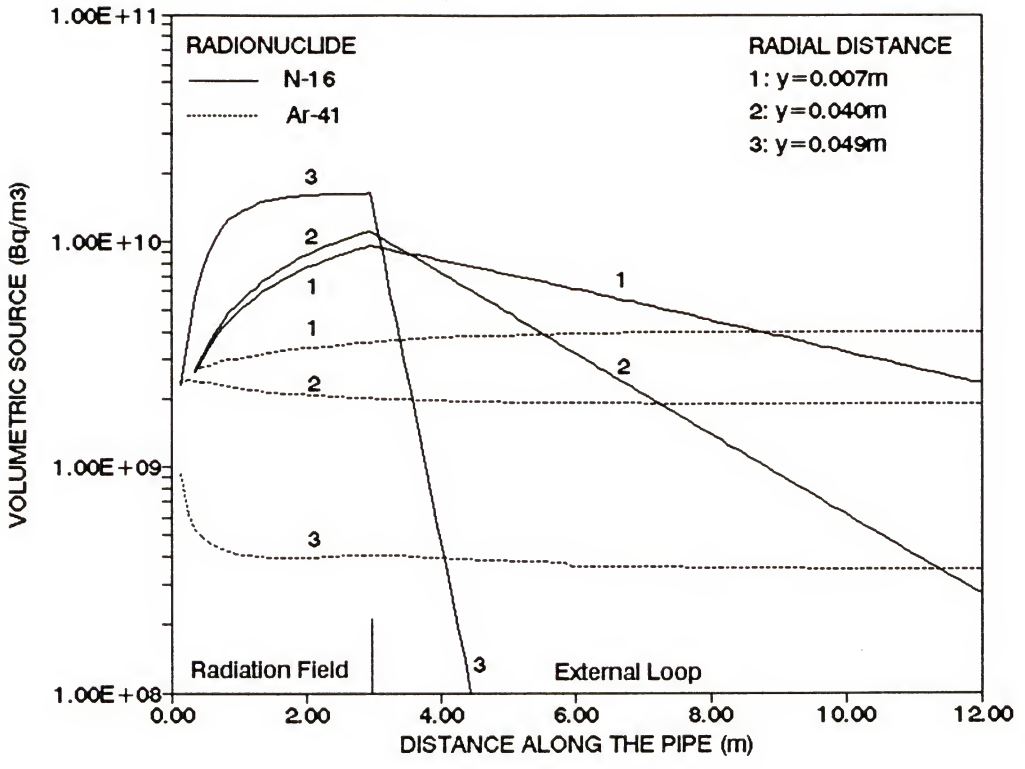


Figure 4-18. Space- and time-dependent argon-41 and nitrogen-16 volumetric radioactive source distributions in air along the pipe (Sample Problem 3).

loop. The radionuclides accumulate in the CVs closest to the centerline. Almost no changes are observed in the volumetric source distributions for lengths greater than 7.0 m. After this point the fluid mass flow rate in the y direction is sufficiently small that a well-developed laminar flow can be considered inside the pipe.

The program RNATPA1 provides the coupling files used by the program GRDOSER.

Gamma Ray Dose Methodology. A problem is designed to compare the results of the program GRDOSER with those provided

by analytical expressions for dose calculations from lines and cylinders with a constant source distributions. The argon-41 volumetric radioactive source distribution in air in the external loop of the pipe is considered constant and equal to $1.0x10^{10}$ Bq m^{-3}. In this way, the external loop can be modeled as a line or cylinder with constant source distribution to be used in the analytical expressions. The detector is positioned at x=7.5m and y=1.0m. No shielding material is used in addition to the wall of the pipe and the source medium considered is the air. The comparative study is presented in Table 4-8.

Dose buildup is included in the total dose equivalent rate. The program GRDOSER uses Berger's formula to calculate buildup factors, while the analytical expressions use Taylor's formula. This table shows the accuracy of the results provided by GRDOSER.

GRDOSER is used to calculate the gamma ray dose equivalent rates from argon-41 and nitrogen-16 radionuclides moving inside the pipe after 3600 s of activation.

The doses are calculated at a distance of 1.0 m from the centerline of the pipe in the y direction for the entire extension of the external loop. The geometric dimensions and the distributions of the volumetric radioactive sources are provided by the program RNATPA1. The gamma ray dose equivalent rates are calculated, for the two radionuclides, considering only the pipe, or considering the pipe and 0.20 m

Table 4-8. Gamma ray dose equivalent rate at x=7.5m and y=1.0m from the argon-41 volumetric radioactive source constant and equal to 1.0×10^{10} Bq.m^3 inside the external loop of the pipe (Sample Problem 3).

METHOD (ANALYTICAL SOLUTION AND NUMERICAL SOLUTION)	DOSE EQUIVALENT RATE (Sv/s) UNCOLLIDED	TOTAL
SELF-ABSORBING SOURCE MEDIUM		
Analytical Solution		
Cylinder Approx. 2 [a]	5.11E-09 [f]	5.86E-09
Cylindrical Volume Source [b]	6.26E-09	
Cylinder Approx. 1 [c]	6.85E-09	8.94E-09
Numerical Solution		
GRDOSER	6.04E-09	8.86E-09
NONABSORBING SOURCE MEDIUM		
Analytical Solution		
Line [d]	6.51E-09	8.57E-09
Numerical Solution		
GRDOSER	6.04E-09	8.87E-09
SELF-ABSORBING SOURCE MEDIUM AND ABSORPTION IN ALL LAYERS		
Numerical Solution		
GRDOSER [e]	5.98E-09	8.84E-09

a. Reference 25, p. 31.
b. Reference 26, p. 383.
c. Reference 25, p. 30.
d. Reference 25, p. 14.
e. Includes the air between the pipe and the detector.
f. Read as 5.11×10^{-09}.

of ordinary concrete as the shielding layer. The results are presented in Figs. 4-19 and 4-20.

The gamma ray dose equivalent rates from argon-41 radionuclides in Fig. 4-19 are practically constant along the external loop of the pipe. These dose rate curves are

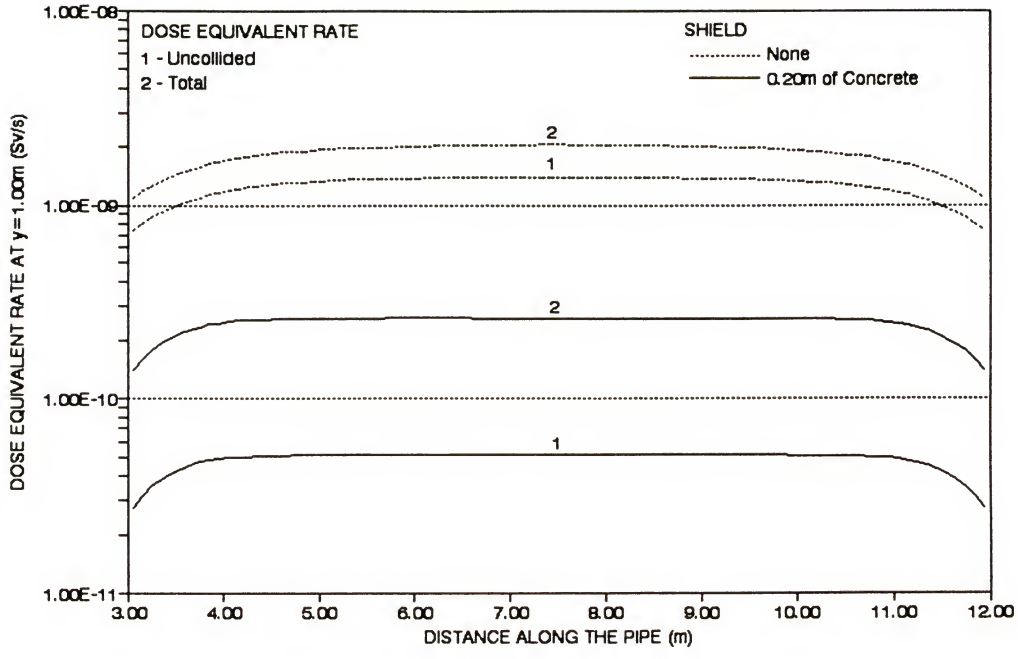


Figure 4-19. Gamma ray dose equivalent rates from argon-41 volumetric radioactive sources at y=1.0m along the external loop of the pipe (Sample Problem 3).

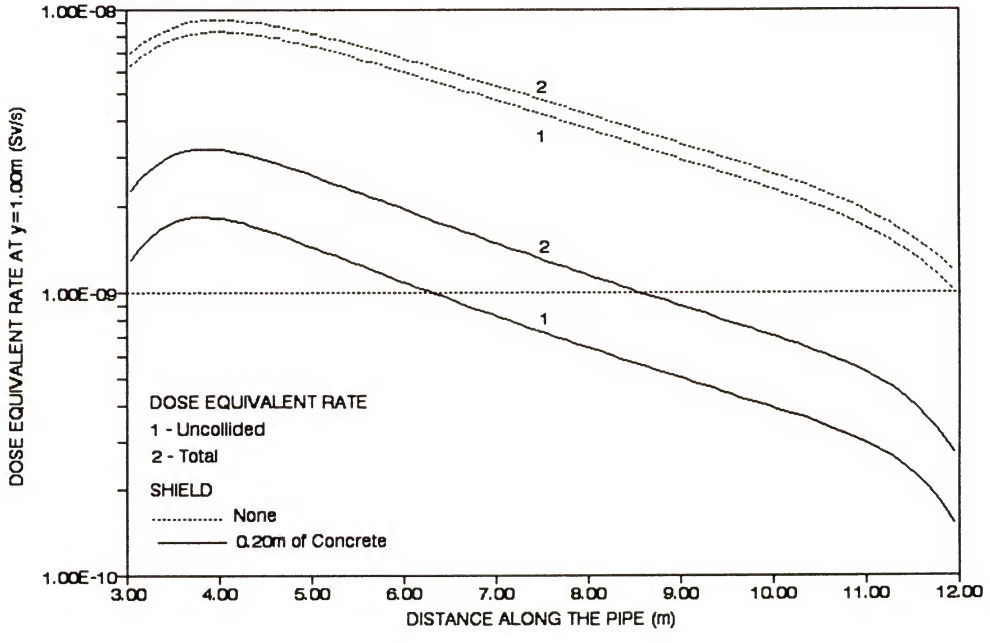


Figure 4-20. Gamma ray dose equivalent rates from nitrogen-16 volumetric radioactive sources at y=1.0m along the external loop of the pipe (Sample Problem 3).

expected because the distributions of argon-41 volumetric sources shown in Fig. 4-18 are constant inside the external loop.

The gamma ray dose equivalent rates from nitrogen-16 radionuclides in Fig. 4-20 are not constant along the external loop of the pipe. These dose rate curves are due to the decay of nitrogen-16 radionuclides, shown in Fig. 4-18, as they are transported along the external loop.

The forms of the dose rate curves closer to the entrance and exit of the external loop of the pipe are explained by the fact that GRDOSER does not take into account, for dose rate calculations, the contributions of volumetric radioactive sources at upstream and downstream positions from the length of the pipe considered.

The results presented in Figs. 4-19 and 4-20 correctly reproduce the gamma ray dose equivalent rates expected from the volumetric radioactive source distributions calculated by RNATPA1.

The solution of sample problem 3 shows how the transport and activation methodology and the gamma ray dose methodology are combined to calculate gamma ray dose equivalent rates from space- and time-dependent source terms in radioactivated fluids flowing through pipes.

The results obtained in sample problem 3, and in the previous sample problems, have been demonstrated that TAM and

GAM can be used to predict the physically expected behavior of radionuclides moving inside pipes.

These observations indicate that the methodologies provide valuable insight to the behavior that radionuclides, moving inside a pipe, have in the complete definition of the radioactive sources inside the pipe, and the radiation fields and doses outside the pipe.

Summary of the Sample Problems

Following the presentation of results, discussion and conclusions of each sample problem, general conclusions about the methodologies and sample problems can be summarized as follows:

a) Analytical expressions might not be sufficiently accurate to calculate the activity induced in fluids flowing through pipes inside radiation fields. Sample problem 1 shows that analytical expressions, considering batch processes, are not able to account for the spatial dependence of the problems. The results indicate that analytical expressions might underestimate the concentrations of a long-lived nuclide throughout the pipe.

b) The program RNATPA1, developed to perform the numerical solutions required in TAM, can be used to predict the space- and time-dependent general behavior of radionuclides activated and transported in fluids flowing through pipes. The discussion of the results from sample

problems 1, 2 and 3 indicates that RNATPA1 is able to simulate the mass transport, production and decay processes of short-lived and long-lived radionuclides in fluids as different as air (gas) and water (liquid).

c) The program GRDOSER, developed to perform the numerical solutions required in GAM, can be used to predict the space- and time-dependent gamma ray dose equivalent rate at a point, outside the pipe, from the space- and time-dependent distribution of gamma ray source terms in the fluid flowing inside of it.

d) In the activation of nonrecirculating fluid (one-pass flow), the rates of growth and decay of short-lived radionuclides are greater than those of long-lived nuclides. The results of sample problems 2 and 3 show these behaviors for nitrogen-16 and oxygen-19 in air and in water, and argon-41 in air.

e) The radionuclides produced are transported by the fluid mass transport. How far the radionuclides are transported depends upon the disintegration constant. Radionuclides that are transported move toward the CVs closer to the centerline of the pipe, increasing the concentration in those CVs.

f) For a long-lived radionuclide with a constant production rate (no neutron flux attenuation inside the fluid) in a recirculating fluid, transport and activation are the dominant processes in the definition of the distribution of

radionuclides throughout the pipe. The radionuclides transported accumulate in the control volumes closer to the centerline. The argon-41 volumetric radioactive source distributions in air flowing through the pipes in sample problems 1, 2 and 3 illustrate this behavior.

d) For a short-lived radionuclide with constant production rate (no neutron flux attenuation inside the fluid) in a recirculating fluid, activation and decay are the dominant processes in the definition of the distribution of radionuclides throughout the pipe. The radionuclides decay before being transported and there is almost no increase in the concentration of radionuclides. According to this behavior, the concentrations of radionuclides are larger in the CVs closest to the wall of the pipe because a unit volume of the fluid spend more time inside the radiation field there than in any other position in the radial direction. The nitrogen-16 and oxygen-19 volumetric radioactive source distributions in air and water flowing through the pipes of sample problems 2 and 3 illustrate this behavior.

CHAPTER 5
CONCLUSIONS

In this study two methodologies are developed: the transport and activation methodology, TAM, and the gamma ray dose methodology, GAM. TAM predicts the space- and time-dependent behavior of radionuclides transported and activated inside pipes and can be used to enhance the understanding of the space- and time-dependent mass transport of radionuclides, their production and decay, and the associated volumetric source terms related to radioactivated fluids flowing through pipes. GAM is used cooperatively with TAM and predicts the space- and time-dependent gamma ray dose equivalent rates at a point outside a pipe having radionuclides flowing through it.

TAM and GAM were not developed to solve all cases of mass transport of radionuclides, their production and decay, and the associated dose rates from radioactivated fluids flowing through vessels and pipes. Certain limiting conditions are established for the scope of this work. The conditions of applicability are:

a) Laminar flow of an incompressible fluid in straight pipe;

b) Nonrecirculating or recirculating flow schemes;

c) Time-independent distribution of velocities of the fluid;

d) Space-dependent distribution of a monoenergetic neutron flux;

e) Space- and time-dependent activation process of a single parent nuclide through the pipe where the neutron-gamma process is the activation reaction of interest;

f) Space- and time-dependent transport and decay of a single radionuclide throughout the pipe; and

g) Space- and time-dependent gamma ray dose rate, calculated outside the pipe, from the space- and time-dependent distribution of the dynamic sources inside of it.

The methodologies and conditions established for the scope of this work provide adequate solutions for many practical cases and can be easily extended to include other situations of interest.

Numerical techniques are used in the methodologies because analytical expressions have been demonstrated to be limited for solving the space- and time-dependent problems addressed in this dissertation. The numerical calculations required by TAM and GAM are performed by the computer programs RNATPA1 and GRDOSER. RNATPA1 includes the numerical solutions of TAM while GRDOSER includes those of GAM. The programs are designed to solve problems addressed by this dissertation within the conditions established above. The program architectures are based on subroutines that can be easily

modified or extended to include solutions for other situations involving space- and time-dependent cases of mass transport of radionuclides, their production and decay, and the associated dose rates for fluids flowing through vessels and pipes. The program architectures, and the possibilities they offer to be modified and extended, make RNATPA1 and GRDOSER flexible frameworks for users.

The methodologies are used to solve three sample problems. The results show good concurrence when compared with those from analytical expressions for simple cases, and are physically consistent for more complex situations.

The solutions obtained with TAM provide insight to the effects of various parameters (i.e., number of control volumes, flow scheme, number of cycles, activation time, and disintegration constant) on the general behavior of radionuclides transported and activated inside pipes. The numerical simulation of the results of the transport and activation processes inside pipes reveal that:

a) The concentration of the radionuclides produced in the fluid increases in the CVs closer to the centerline; the changes in concentration depends on the half-lives of the radionuclides and/or fluid materials;

b) Activation and decay are the dominant processes in the concentration changes of short-lived radionuclides in the CVs closer to the centerline (i.e., transport has a minor role);

c) Activation and transport are the dominant processes in the concentration changes of long-lived radionuclides in the CVs closer to the centerline (i.e., decay has a minor role);

d) For recirculating fluids the concentration increases of short-lived in the CVs closer to the centerline are less pronounced than those of long-lived radionuclides; and

e) The motion and concentration changes of radionuclides determine the space- and time-dependent volumetric radioactive source distributions inside the pipes.

GAM uses results from TAM to perform its calculations. GAM reproduces adequately the expected gamma ray doses from the distributions of radionuclides calculated in TAM.

It has been demonstrated in the theoretical development that TAM and GAM are able to simulate the general behavior of radionuclides transported and activated inside pipes and the results they provide can be used to enhance the understanding of the phenomena addressed in this dissertation. The best way, however, to validate what has been theoretically demonstrated would be by comparing the results of TAM and GAM with experimental data. This comparison is not possible presently because no space-time dependent data is available from the open literature and the required experimental program is beyond the scope of this work. A schematic diagram of an apparatus that could be used to provide experimental data for verification tests of TAM and GAM is suggested in Appendix D.

The apparatus would include an activation fluid, a closed circuit pipeline crossing a reactor core, gamma ray detectors, a flow rate meter, a fluid circulating pump, pitot tubes, and evacuated containers. A plenum can be inserted in the pipeline immediately before the entrance to the core and the fluid circulating pump must be positioned before this plenum. This layout assures that the circulating fluid is mixed before entering the reactor core. The collection of samples from the radioactivated fluid and the gamma ray dose measurements, outside the pipe, can be performed at any position along the external loop between the exit of the core and the fluid circulating pump. Pitot tubes are used to draw samples from the radioactivated fluid into the evacuated containers. These pitot tubes can be positioned at different longitudinal and radial positions. The measured activity of a container filled with the fluid divided by its volume gives the volumetric induced activity from which the volumetric concentration of radionuclides can be obtained at the position of the pitot tube. The activation time (i.e., the time at which the sample is drawn) is defined by the user. In this way the space- and time-dependent distribution of radionuclides could be mapped inside the external loop of the pipe, and the space- and time-dependent gamma ray dose equivalent rates could be mapped outside the external loop of the pipe.

This work addresses the issue of improved predictions of the behavior of radioactive fluids subject to space-time

coupled effects. The main contributions of this dissertation to nuclear engineering and science are summarized as follows:

a) Development of TAM to predict the space- and time-dependent behavior of radionuclides transported and activated inside pipes, and to enhance the understanding of the mass transport of radionuclides, their production and decay, and the associated volumetric source terms related to radioactivated fluids flowing through pipes.

b) Development of GAM to calculate the space- and time-dependent gamma ray dose equivalent rates, outside pipes, from the space- and time-dependent distributions of volumetric source terms in radioactivated fluids flowing through them.

c) Development of the computer programs RNATPA1 and GRDOSER to perform the numerical solutions required by TAM and GAM. Both programs provide very flexible frameworks for users and provide a unified package for PC-based calculations addressed to designers in the field of radiation protection and shielding.

APPENDIX A
COMPUTER PROGRAMS RNATPA1 AND GRDOSER

Radionuclide Activation and Transport in Pipe

The computer program Radionuclide Activation and Transport in Pipe, RNATPA1, was developed to incorporate the transport and activation methodology presented in Chapter 3 to calculate the space- and time-dependent transport and activation radionuclides inside a pipe. The program is appropriate for straight pipes, laminar flows, axisymmetric geometries, and single activation process of a single parent nuclide.

FORTRAN, including several features of FORTRAN 77, is used as the programming language. The program is compiled using Microsoft FORTRAN version 5.0.

The architecture of the program is based on subroutines. The FORTRAN statement ENTRY is used to delimit member subroutines inside the subroutines. Since the ENTRY statement allows that a member subroutine be considered as an independent subroutine, the name subroutine will be used to identify both subroutines and member subroutines.

The computer program RNATPA1 has a program MAIN, a common part INVAR.FOR, and the subroutines FFLOW, ALGOR, ACTRA, PRINTER, and ADAPT. The listing structure of the RNATPA1 is

shown in Fig. A-1. The listing of the computer program is presented in Appendix B. The list of the Fortran variables is included in the program MAIN. Headings are provided in the subroutines to identify the main steps of the calculations and to allow the reader follow the explanations about the program. Figure A-2 shows the flowchart of the sequence in which the subroutines are used by the computer program RNATPA1.

Common Part INVAR.FOR

The number of grid lines ID in the x direction, the number of grid lines JD in the y direction, and the number of variables NFD used in a specific problem are defined in INVAR.FOR. Also, INVAR.FOR includes the COMMON, the DIMENSION, and the EQUIVALENCE statements for all the important program variables. The INVAR.FOR must be designed for each different problem to be solved.

Program MAIN

The program MAIN starts the computation and controls the sequence of operations calling the subroutines according to the flowchart displayed in Fig. A-2.

Subroutine FFLOW

The subroutine FFLOW solves the governing differential equations for fluid flow. The finite-difference method is used to transform these equations into algebraic equations

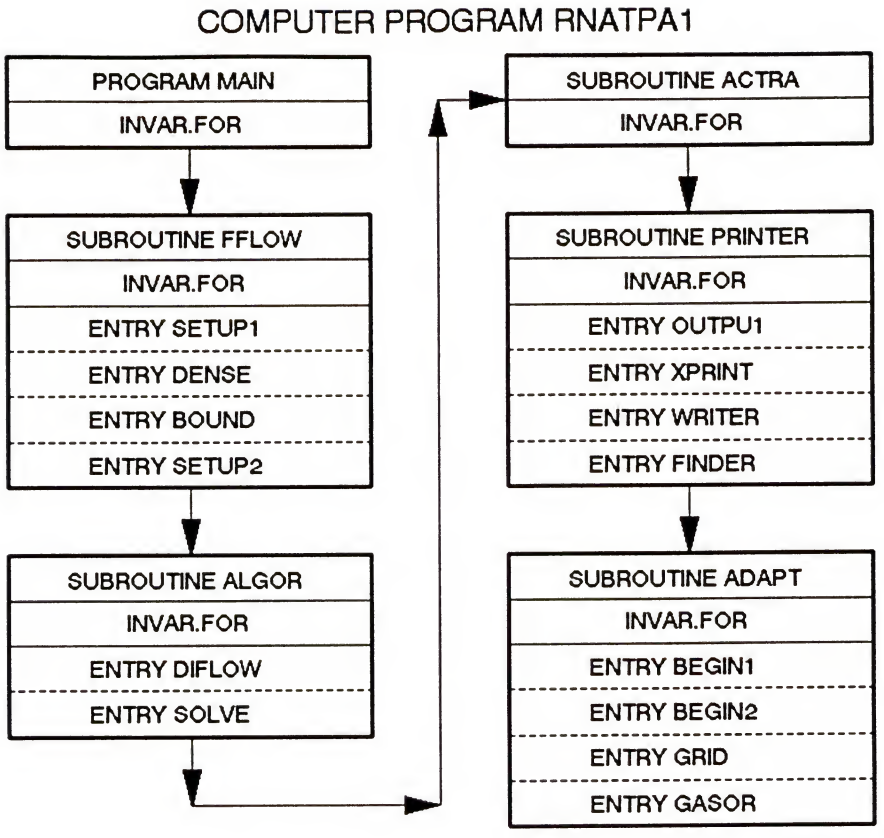


Figure A-1. Listing structure of the computer program RNATPA1.

involving the unknown values of the velocities U(I,J) in the x direction, the velocities V(I,J) in the y direction, and the temperatures T(I,J). These algebraic equations, known as discretization equations, are formed by integrating the Eqs. (3-2), (3-3), and (3-4) over the control volumes constructed around the grid points (I,J).

The numerical technique used to solve the discretization equations is described in detail in references 11 to 16. Because the subroutine FFLOW was written based on these references, only the main features of the member subroutines will be explained in this work.

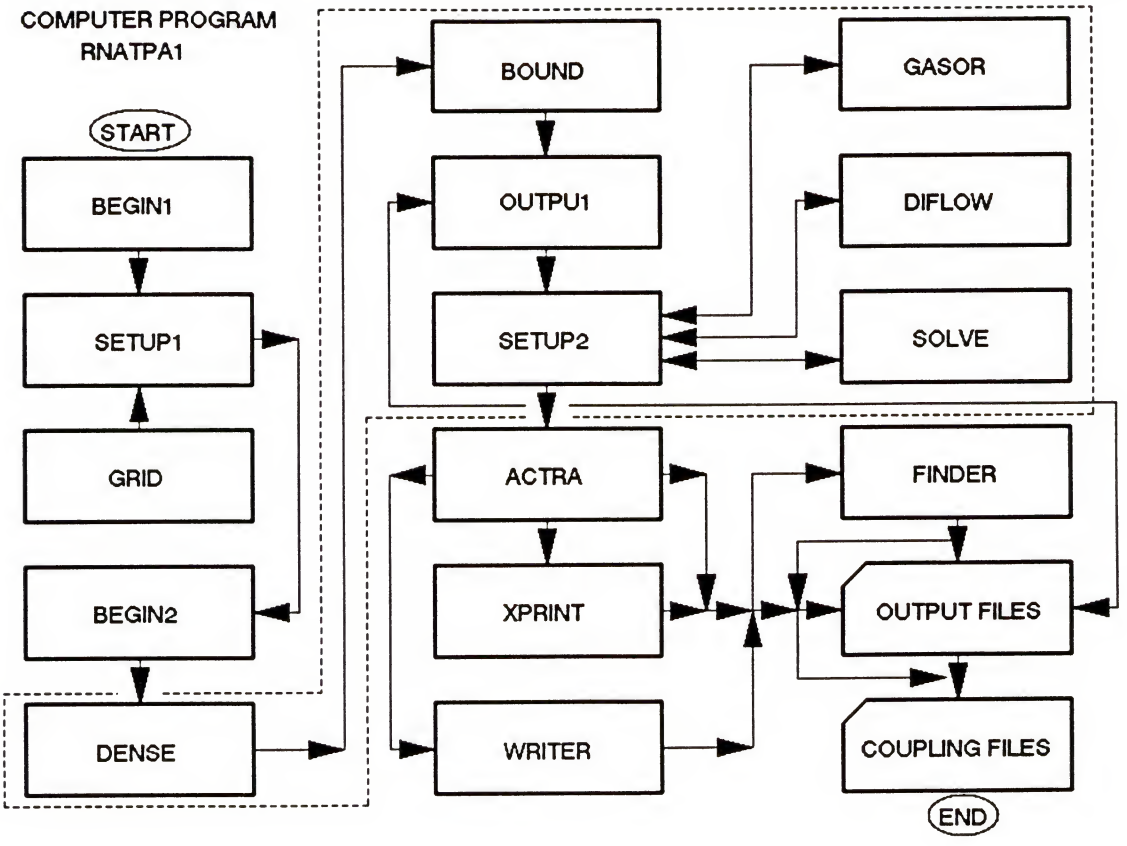


Figure A-2. Flowchart of the sequence in which the subroutines are used by the computer program RNATPA1.

The final values provided by the subroutine FFLOW, for each control volume, are the density RHO(I,J), the velocities U(I,J) and V(I,J), and the temperature T(I,J). The results provided by FFLOW have been demonstrated to be in good agreement with those provided by the software of reference 15.

Subroutine SETUP1. The function of SETUP1 is to calculate the values of the numerous geometric quantities. This subroutine uses data supplied by the user through BEGIN1 and GRID in the subroutine ADAPT.

Subroutine DENSE. The purpose of DENSE is to evaluate the densities RHO(I,J) at all grid points as a function of the

density of reference RHOREF, of the temperature of reference TREF, and of the temperatures T(I,J). The subroutine DENSE performs its task using Eq. (3-5).

Subroutine BOUND. This subroutine provides values for velocities and temperatures at the grid lines in the boundaries of the calculation domain and for fluid mass flow rates at the entrance and exit of the pipe. The velocities U(I,1), U(L1,J) and V(L1,J), the temperatures T(I,1) and T(L1,J), and the fluid mass flow rates FLOWIN, at the entrance of the pipe, and FLOWOU, at the exit of the pipe, are calculated in BOUND. FLOWIN is used to calculate the velocities U(L1,J) to assure that the fluid mass flow rates FLOWIN and FLOWOU are the same.

Subroutine SETUP2. The subroutine SETUP2 integrates the Eqs. (3-2), (3-3), and (3-4) over each of the control volumes constructed around the grid points to provide the coefficients AIM(I,J), AIP(I,J), AJM(I,J), AJP(I,J), AP(I,J), and CON(I,J) for the discretization equations. SETUP2 calls DIFLOW to calculate AIM(I,J), AIP(I,J), AJM(I,J), and AJP(I,J). If the source term for the momentum equation in the y direction is different from that of Eq. (3-3), and if there is a source term for the temperature equation given by Eq. (3-4), SETUP2 will call the subroutine GASOR to obtain the new data for AP(I,J) and CON(I,J) supplied by the user. The subroutine SOLVE is then used to calculate the velocities U(I,J) and V(I,J), and the temperatures T(I,J) for all control volumes.

The subroutine SETUP2 also stops the iterative process when the maximum number of iterations (LAST) is reached. The calculations carried out in the subroutines enclosed by the dashed line in Fig. A-2 are repeated until the desired convergence criterion is reached.

Subroutine ALGOR

Subroutine ALGOR comprises in its member subroutines the basic algorithms used to calculate the coefficients for the discretization equations and to solve the discretization equations.

Subroutine DIFLOW. This subroutine provides the dimensionless term ACOF needed to calculate the coefficients AIM(I,J), AIP(I,J), AJM(I,J), and AJP(I,J) in SETUP2. The derivation of the expression to evaluate ACOF is explained in detail in reference 13.

Subroutine SOLVE. The task of SOLVE is to perform the iterative solution of the discretization equations whose coefficients are given by SETUP2 and DIFLOW. To calculate the velocities U(I,J) and V(I,J), and the temperatures T(I,J), the subroutine SOLVE uses the algorithm called TDMA (TriDiagonal-Matrix Algorithm). The solutions of linear algebraic equations using the TDMA algorithm are presented and explained in detail in references 12 to 15.

Subroutine ACTRA

The most important calculations of the transport and activation methodology are executed in subroutine ACTRA. This subroutine calculates the space- and time-dependent transport and activation of radionuclides in fluids flowing through a pipe, and the volumetric radioactive sources VOSO(I,J) created by the moving radionuclides inside the pipe. Also, ACTRA calculates the production rate of radionuclides PRORA(I,J) and the total volumetric radioactive sources TVOSO(I) at the stations, and creates the coupling files GEOMETRY.INP and VSOURCES.INP. Another feature in ACTRA is the control of the types of output to be printed out according to the instructions supplied by the user in subroutine ADAPT.

To execute its tasks, ACTRA solves the coupling equations, the radioactivation equations, and the volumetric source equations presented in Chapter 3.

Coupling equations. Equations (3-6) through (3-17) are used to calculate the fluid mass flow rates FMFR(I,J) in the control volumes, the fluid mass flow rates FTACV(I,J) transferred to or from the control volumes, and the times XTIME(I,J) that the fluid spends inside the control volumes. The FTACV(I,J) and the XTIME(I,J) couple the fluid flow equations and the radioactivation equations permitting the space- and time-dependent calculation of the activation and transport of radionuclides inside the pipe.

Radioactivation equations. Subroutine ACTRA was written to calculate the space- and cycle-dependent activation and the space- and time-dependent activation. The variables LCYCLE, LATIME, NCYCLE, and LATREC, defined by the user in ADAPT, are used in ACTRA to control the activation scenario and the recirculation of the fluid.

In the cycle-dependent activation scenario, the first step is the computation of the initial radionuclide concentrations XNDACT(1,J), XNDACT(I,1) and XNDACT(I,M1) in the boundaries, and XNDACT(I,J) in the other control volumes. If the fluid recirculates, XNDACT(1,J) will be the weighted average of XNDACT(L1,J). In the first cycle, XNDACT(I,J) are equal to the values supplied by the user in ADAPT. In the subsequent cycles, XNDACT(I,J) are equal to the radionuclide concentrations of the previous cycle.

After that, Eqs. (3-18), (3-19) and (3-26) through (3-32) are used to calculate the final radionuclide concentrations XNDACT(I,J) in the control volumes. Since the radionuclide concentrations are updated with each cycle, the same array XNDACT(I,J) is used to store both the initial and final concentrations. When the fluid recirculates, the computational procedure is repeated until the total number of cycles NCYCLE is completed.

In the time dependent-activation scenario, the first step is the computation of the time controller variables XTIME1(I,J), XTIME2(I,J), XTIME3(I,J) and XTIME4(I,J), given

by Eqs. (3-20) through (3-23), and the initial radionuclide concentrations XNDACT(I,J) and XNDPRE(I,J). For the activation time ATIME equal to the initial activation time ATI, XNDACT(I,J) and XNDPRE(I,J) are equal to the values supplied by the user in ADAPT. In the subsequent ATIME, the initial XNDACT(I,J) are equal to the XNDPRE(I,J), the final radionuclide concentrations of the previous ATIME.

The accumulation of the activation time ATIME is then started, the radionuclide concentrations XNDACT(I,1) and XNDACT(I,M1) in the boundaries are defined, and the final radionuclide concentrations XNDACT(I,J) are calculated using Eqs. (3-18), (3-19), and (3-26) through (3-32). The time controller variables XTIME1(I,J) are checked for all control volumes to verify if XNDACT(I,J) will be updated or not. Following the calculation of XNDACT(I,J) and if the fluid recirculates, the time controller variables XTIME1(I,J) and XTIME2(J) will be modified according to Eqs. (3-24) and (3-25). Finally, the activation time ATIME is incremented by the time step DAT and the computation procedure repeated until the final activation time ATF is reached.

Volumetric source equations. After the radioactivation equations have been solved, the subroutine ACTRA uses XNDACT(I,J) and Eq. (3-33) to calculate the volumetric radioactive sources VOSO(I,J). The next steps performed in ACTRA are the calculations of the production rate of radionuclides PRORA(I,J) for the control volumes and of the

total radioactive volumetric sources TVOSO(I) for the stations. Equations (3-34) and (3-35) are used to perform these tasks.

Output files. Another task executed in ACTRA is the control of the output files. The variables LWRITE and LFIND, defined by the user in the subroutine ADAPT, indicate which member subroutine of PRINTER must be called from ACTRA to create the desired output file.

Coupling files. The last task performed by ACTRA is to print out the coupling files GEOMETRY.INP and VSOURCES.INP. The GEOMETRY.INP file stores the geometric dimensions X(I), Y(J), XCV(I) and ARX(J). The VSOURCES.INP file stores the volumetric radioactive sources VOSO(I,J). These two files are used by the computer program GRDOSER developed for the gamma ray dose methodology described in Chapter 3.

Subroutine PRINTER

The subroutine PRINTER embodies the member subroutines OUTPU1, XPRINT, WRITER and FINDER. The subroutine OUTPU1 and part of the subroutine XPRINT are always used to print out the output files. The format in which the data are presented are controlled by the variables LWRITE and LFIND.

Subroutine OUTPU1. This subroutine provides the headings for the output files. The identification of the problem, the coordinate system, the number of control volumes, the type of activation chosen, and the variables that control the

convergence of the iterative calculation in the subroutine FFLOW are printed out by OUTPU1.

Subroutine XPRINT. The values of the variables for each control volume are printed out by XPRINT. The outputs are arranged in matrices. Index I varies along the width of the listing (horizontal direction) and index J varies along the height of the listing (vertical direction).

Subroutine WRITER. The task performed by this subroutine is the same as that of XPRINT. The difference is that in WRITER, index I varies along the height of the listing and the index J varies along the width of the listing (i.e., the order is transposed). If the user desires, both outputs will be printed.

Subroutine FINDER. The subroutines XPRINT and WRITER print out the values of the variables at the grid points or at the interfaces of the control volumes. To provide more freedom for the user, the subroutine FINDER interpolates values between the values at neighboring grid points. The only limitation of FINDER is that it cannot be used to print out interpolated values for velocities U(I,J) and V(I,J) because they are not calculated at the grid points.

Subroutine ADAPT

The subroutine ADAPT and the invariant part INVAR.FOR have to be designed to describe each problem to be solved.

Because of this, the information supplied by the user in INVAR.FOR and in ADAPT must agree.

The subroutine ADAPT has four member subroutines performing different tasks needed to define a specific problem. It could be tedious, at this point, to explain all of these tasks since Appendix B presents a complete listing of ADAPT with all necessary headings. It will be helpful if the reader refers to that appendix while reading this section. Only the main features of each member subroutine will be presented here. Whenever possible, the DATA statement is used in ADAPT to define a variable.

Subroutine BEGIN1. The data supplied in BEGIN1 must specify the problem and the way to solve it. To define the problem the user provides information related to the characteristics of the fluid, geometry of the pipe, number of control volumes, and grid. To specify the way in which the problem will be solved, the user provides information related to the number of files to be opened, variables to be calculated and printed out, iterations planned, convergence criterion, type of activation to be calculated, and types of output files desired. Also, the subroutine BEGIN1 sets up the default values for the internal variables.

Subroutine BEGIN2. The initial profiles of velocities U(I,J) and temperatures T(I,J) are defined by the user in BEGIN2. If the restarting option, controlled by the variable LSTART, is to be used, BEGIN2 will supply the initial profiles

of U(I,J), V(I,J), T(I,J), RHO(I,J), PC(I,J), and P(I,J) reading their values from the TEMPFILE.111 file created by the subroutine OUTPU1. The radiation field XPHI(I,J) and the initial radionuclide concentrations XNDACT(I,J) and XNDPRE(I,J) are also defined in BEGIN2.

Subroutine GRID. The computer program RNATPA1 assumes that the widths of the control volumes are equal in each coordinate axis. This means that all XCV(I) are equal and all YCV(J) are also equal. If this assumption is not adequate for a problem, the user can modify it. To do so, the logical variable LGRID must be defined in BEGIN1 and GRID has to be redesigned. When LGRID is defined as true, SETUP1 calls the subroutine GRID that calculates the variables X(I), XU(I), Y(J), and YV(J) according to the new distributions of control volumes.

Subroutine GASOR. The source terms for the governing fluid flow differential equations are supplied by the subroutine GASOR. The computer program RNATPA1 was designed in such a way that it incorporates the source term for Eq. (3-3). Since no source terms exist in Eqs. (3-2) and (3-4) (i.e., laminar flow and no heat generation inside the pipe), the user does not need to design GASOR. However, if the RNATPA1 is modified to include the option to solve turbulent flow and if there is heat generation inside the pipe, a new subroutine GASOR will be necessary to incorporate the source terms for momentum and energy equations. The new subroutine

GASOR must supply the coefficients AP(I,J) and the constant terms CON(I,J) obtained from the linearization of each new source term. The linearization of a source term is explained in details in references 11 to 15.

Gamma Ray Dose Equivalent Rate

The computer program Gamma Ray Dose Equivalent Rate, GRDOSER, was developed to incorporate the gamma ray dose methodology presented in Chapter 3 to calculate the gamma ray dose equivalent rate from moving radionuclides inside pipes. GRDOSER assumes that a multilayered shield exists between the point radioactive sources located inside the control volumes and the position of the detector.

FORTRAN, including several features of FORTRAN 77, is used as the programming language. The program is compiled using Microsoft FORTRAN version 5.0.

The architecture of the GRDOSER is based on subroutines. It has a program MAIN, a common part INVAG.FOR, and the subroutines INPUT, OUTPUT, DOSERATE, and INTRPL. The listing structure of the GRDOSER is shown in Fig. A-3. The listing of the computer program is presented in Appendix C. The list of Fortran variables is included in the program MAIN. Headings are provided in the subroutines and in the input file to identify the main steps of the calculations or the data supplied, and to allow the reader to follow the explanations of the program.

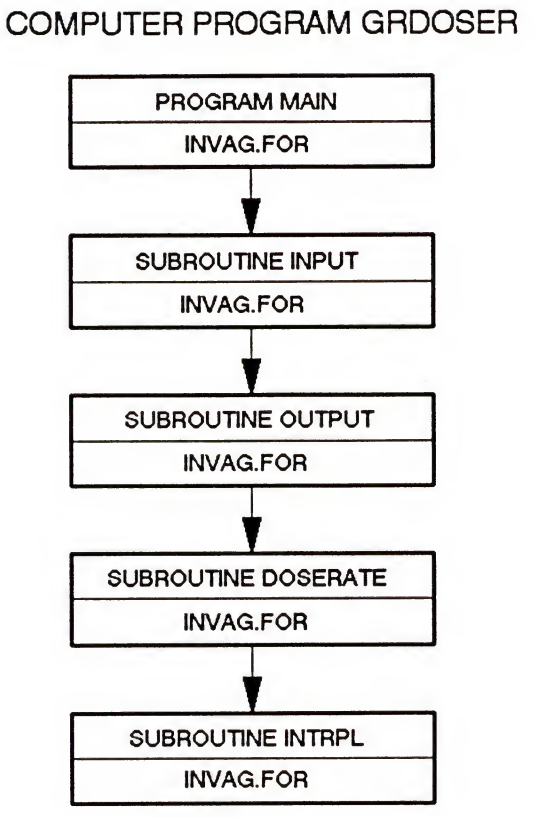


Figure A-3. Listing structure of the computer program GRDOSER.

The flowchart of Fig. A-4 illustrates the sequence in which the subroutines are used by the computer program GRDOSER. The coupling files and the input file are used to define the problem to be solved. The coupling files GEOMETRY.INP and VSOURCES.INP are provided by the program RNATPA1. The GRDOSER.INP input file is designed by the user.

Invariant Part INVAG.FOR

The number of grid lines ID in the x direction, the number of grid lines JD in the y direction, the number of angular sectors NS, the number of shielding layers NL, the

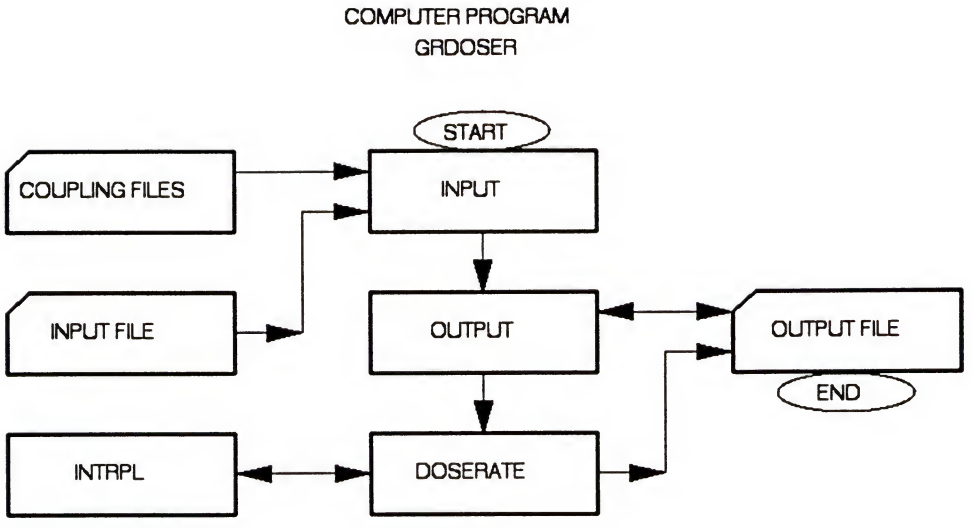


Figure A-4. Flowchart of the sequence in which the subroutines are used by the computer program GRDOSER.

number of gamma rays NP, the number of radioactive volumetric sources NVS, and the COMMON statements for all of the important program variables are defined in INVAG.FOR.

The common part INVAG.FOR must be designed for each specific problem to be solved. As the program GRDOSER reads output files from the program RNATPA1, the values of ID and JD, defined in both programs, must be the same.

Program Main

The program MAIN starts the computation and controls the sequence of operations calling the subroutines according to the flowchart displayed in Fig. A-4.

Subroutine INPUT

The subroutine INPUT reads in the data from the coupling files GEOMETRY.INP and VSOURCES.INP, and from the GRDOSER.INP input file.

GEOMETRY.INP file. This file supplies the geometric dimensions X(I), Y(J), XCV(I), and ARX(J) for the problem.

VSOURCES.INP file. The space- and time-dependent volumetric radioactive sources calculated in the RNATPA1 are read from this file.

GRDOSER.INP file. This file must be designed for each problem to be solved. Since this is also required by the invariant part of the program, the information supplied by the user in INVAG.FOR and in GRDOSER.INP must be consistent.

Appendix C presents a complete listing of the subroutine INPUT and of the GRDOSER.INP input file. Headings are provided in GRDOSER.INP to identify the order in which the data are read.

Subroutine OUTPUT

OUTPUT prints out the reference data. It creates the GRDOSER.OUT file that allows the user to verify the data supplied in the input file.

Subroutine DOSERATE

The gamma ray dose methodology, explained in Chapter 3, was incorporated in subroutine DOSERATE. This subroutine is

presented in Appendix C with enough headings to permit the reader follow the sequence of calculation.

The calculation is carried out for each control volume, each point radioactive source derived from each volumetric radioactive source, and each gamma ray emitted by the point radioactive source. To save memory locations and to optimize the computer program, whenever possible single variables were used instead of arrays of variables with more than one dimension. Because of this, the reader may observe that some indexes used in the formulas derived in Chapter 3 were omitted in the subroutine DOSERATE.

The initial tasks of DOSERATE are to calculate geometric dimensions and strengths of the point radioactive sources. The geometric dimensions are the distances DIST1(J,K,NLC) and DIST2(J,K,NLC) through the shielding layers, and the distance DCVD from the grid point inside the control volume to the detector. These distances are used in Eqs. (3-36), (3-37), and (3-40). The strength of a point radioactive source, defined by the variable SOURCE, is calculated from Eq. (3-39).

After, the effective atomic number ZBAR for the multilayered shield is computed according to Eq. (3-36). The ZBAR and the energy of the gamma ray, defined by the variable ENERGY, are transmitted to the subroutine INTRPL that calculates the buildup factor B and the mass energy absorption coefficient XMUEN for the gamma ray in the water.

Finally, the subroutine DOSERATE uses Eqs. (3-40) through (3-43) to calculate the gamma ray dose equivalent rate DOSET at the position of the detector.

To calculate the total gamma ray dose equivalent rate TDOSE given by Eq. (3-44), the computation procedure described to this point is repeated for all gamma rays emitted from each point radioactive source, for all point radioactive sources inside each control volume, and for all control volumes.

The subroutine DOSERATE prints out the calculation summaries, including the number of control volumes and TDOSE, in the GRDOSER.OUT output file.

Subroutine INTRPL

For each gamma ray, the subroutine INTRPL calculates the buildup factor B in the multilayered shield, and the mass energy absorption coefficient XMUEN in the water. The buildup factor is calculated using Eq. (3-38).

To perform its tasks, the subroutine INTRPL interpolates the values of the variables ABAR, BBAR and XMUEN in the interpolation tables designed by the user in the GRDOSER.INP input file and read in by the subroutine INPUT.

APPENDIX B
LISTING OF THE COMPUTER PROGRAM RNATPA1

To illustrate the application of the computer programs RNATPA1 and GRDOSER a specific problem was designed. A pipe 12.0 m long has 3.0 m inside a radiation field with fast neutron flux equal to 1.0×10^{15} n m^{-2} s^{-1} and 9.0 m in the external loop shielded by ordinary concrete with 0.2 m of thickness. The internal diameter of the pipe is 0.1 m and its wall is iron with 0.007 m of thickness. Air is flowing through the pipe with initial velocity equal to 0.3 m s^{-1} in the longitudinal direction (i.e., the x direction). The temperatures of the air and of the wall of the pipe are the same and equal to 300.0 K.

The program RNATPA1 was used to calculate the radioactive volumetric sources that the nitrogen-16 radionuclides, produced by the fast neutron activation of the oxygen-16 nuclides in the air, generate along the pipe, and to provide the coupling files to be used with the computer program GRDOSER shown in the Appendix B.

The listings for RNATPA1, the common part INVAR.FOR, and the output file are presented below. RNATPA1 comprises a program MAIN and the subroutines FFLOW, ALGOR, ACTRA, PRINTER, and ADAPT. The list of Fortran variables is included in the

program MAIN. Each subroutine embodies member routines using ENTRY statements. The INVAR.FOR includes the COMMON, the DIMENSION, and the EQUIVALENCE statements for all the important program variables. The subroutines have headings to identify the main steps in the calculations.

The subroutine ADAPT and the invariant part INVAR.FOR were designed to solve the suggested problem and show how to incorporate the data into the program. Twenty control volumes were used in the x direction (5 inside the radiation field and 15 in the external loop). Five control volumes were used in the y direction. The radioactive volumetric sources stored in the VSOURCES.INP output file correspond to an activation time of 3600.0 s with recirculating flow.

Program RNATPA1

Program MAIN

```
C*****************************************************************C
C                                                                 C
C     PROGRAM RNATPA1 - RADIONUCLIDE ACTIVATION AND TRANSPORT     C
C                       IN PIPES      (AXISYMMETRIC GEOMETRY)     C
C                                                                 C
C             S. Gavazza - University of Florida - 1992           C
C                                                                 C
C*****************************************************************C
      PROGRAM MAIN
C*****************************************************************C
$INCLUDE:'INVAR.FOR'
C*****************************************************************C
c
c LIST OF FORTRAN VARIABLES
c
c ACP ......... constant-pressure specific heat of the fluid
c ACOF(I,J) ... dimensionless term needed to calculate the
c               coefficients for the discretization equations
c AIM(I,J) .... coefficient for the discretization equations
c AIP(I,J) .... coefficient for the discretization equations
c AJM(I,J) .... coefficient for the discretization equations
c AJP(I,J) .... coefficient for the discretization equations
```

```
c AK ..... thermal conductivity of the fluid
c ALAMB ..... disintegration constant for the daughter radionuclide
c AMU ..... viscosity of the fluid
c AMUT ..... AK/ACP
c AP(I,J) ..... coefficient term for the linearization of the source
c               in the governing fluid flow equations
c ARX(J) ..... area of the face of the main control volume normal to
c               the x direction
c ARXJ(J) ..... the part of ARX(J) that overlaps on the control volume
c               for V(I,J)
c ARXJP(J) .... the part of ARX(J) that overlaps on the control volume
c               for V(I,J+1)
c ATF ..... final activation time
c ATI ..... initial activation time
c ATIME ..... activation time
c BLAMB ..... 1.0/ALAMB
c CON(I,J) .... constant term for the linearization of the source in
c               the governing fluid flow equations
c CRIT ..... convergence criterion
c DAT ..... time step to calculate the time dependent activation
c DT ..... time step to solve the governing fluid flow equations
c DU(I,J) ..... coefficient for the pressure in the equation to
c               correct the U velocity
c DV(I,J) ..... coefficient for pressure in the equation to correct
c               the V velocity
c F(I,J,NF) ... variables to be calculated
c F3(I) ..... interpolated value of a variable in the FINDER
c               algorithm
c FLOWIN ..... fluid mass flow rate at the entrance of the pipe
c FLOWOU ..... fluid mass flow rate at the exit of the pipe
c FMFR(I,J) ... fluid mass flow rate in the control volume
c FRA ..... fraction to calculate the number density of the
c               parent nuclide
c FT ..... fraction of the fluid mass flow rate transferred from
c               each control volume
c FTACV(I,J) .. fluid mass flow rate transferred to or from the
c               control volume
c FX(I) ..... interpolation factor to calculate the density at the
c               interface XU(I)
c FXM(I) ..... interpolation factor to calculate the density at the
c               interface XU(I)
c FY(J) ..... interpolation factor to calculate the density at the
c               interface YV(J)
c FYM(J) ..... interpolation factor to calculate the density at the
c               interface YV(I)
c GAM(I,J) .... diffusion coefficient for the fluid flow equations
c HEAD ..... heading for the files
c I ..... index denoting the position in the x direction
c ICOUNT ..... iteration counter
c ICRIT ..... controller for the convergence criterion
c ID ..... number of I locations allowed in array dimensions and
c               equal to the number of control volumes in the
c               x direction plus two
c IDK ..... controller for the positions in the FINDER algorithm
c IFLAG1 ..... controller to print out the heading
c IPREF ..... grid point index used as reference for the pressure
c IST ..... first internal point in the I array
c ITER ..... iteration counter
c IT ..... index denoting the position in the x direction of the
c               control volume to verify the temperature convergence
c IU ..... index denoting the position in the x direction of the
c               control volume to verify the U velocity convergence
```

```
c J ..... index denoting the position in the y direction
c JD ..... number of J locations allowed in array dimensions and
c              equal to the number of control volumes in the
c              y direction plus two
c JPREF ..... grid point index used as reference for the pressure
c JST ..... first internal point in the J array
c JT ..... index denoting the position in the y direction of the
c              control volume to verify the temperature convergence
c JU ..... index denoting the position in the y direction of the
c              control volume to verify the U velocity convergence
c JUMP ..... controller to print out the values of the variables to
c              verify the convergence when solving the governing
c              fluid flow equations
c JUMPC ..... controller to print out the values of the variables
c              when calculating the activation as a function of the
c              number of cycles
c JUMPT ..... controller to print out the values of the variables
c              when calculating the activation as a function of the
c              time
c L1 ..... value of the I in the grid line at the right boundary
c L2 ..... L1-1
c L3 ..... L1-2
c LAST ..... maximum number of iterations
c LATIME ..... controller for the activation as a function of the
c              space and the time
c LATREC ..... controller for the recirculating flow when the
c              activation is function of the space and the time
c LBLK(NF) .... controller to use the block-correction scheme to solve
c              the governing fluid flow equation for a variable
c LCYCLE ..... controller for the activation as a function of the
c              space and the number of cycles
c LFIND(NF) ... controller to use the FINDER algorithm for a variable
c LFINDV ..... controller to use the FINDER algorithm
c LFLAG2(NF) .. controller to print out the positions in the FINDER
c              algorithm
c LPRINT(NF) .. controller to print out the values of a variable
c LSTACT ..... controller to restart the time-dependent activation
c LSTART ..... controller to restart the iterative calculation to
c              solve the governing fluid flow equations
c LSOLVE(NF) .. controller to solve the governing fluid flow equation
c              for a variable
c LSTOP ..... controller to stop the RNATPA1 program
c LWRITE ..... controller to use the WRITER algorithm
c M1 ..... value of the J in the grid line at the top boundary
c M2 ..... M1-1
c M3 ..... M1-2
c MAXIJ ..... maximum value between ID and JD
c N1 ..... number of control volumes in the x direction
c N2 ..... number of control volumes in the y direction
c N1N2 ..... total number of control volumes
c NCYC ..... controller for the number of cycles
c NCYCLE ..... total number of cycles
c NCV1...NCVn . number of control volumes in the different regions of
c              the calculation domain in the x direction
c NCVY ..... number of control volumes of the calculation domain in
c              the y direction
c NF ..... index denoting a variable
c NFD ..... number of variables to be calculated
c NFDP ..... NFDP+1
c NFILES ..... number of files to be opened
c NP ..... number of points used in the FINDER algorithm
c NTIMES(NF) .. maximum number of repetitions in the SOLVE algorithm
```

```
c                for a variable
c NVC(I) ..... variable to identify a position in the FINDER
c                algorithm
c P(I,J) ..... pressure at the grid point
c PC(I,J) ..... value of the pressure correction
c PRORA(I,J) .. production rate of radionuclide in the control
c                volume
c PT(I) ....... transformed coefficient in the TDMA
c PT(J) ....... transformed coefficient in the TDMA
c QT(I) ....... transformed coefficient in the TDMA
c QT(J) ....... transformed coefficient in the TDMA
c R(J) ........ radius r for a grid point
c RELAX(NF) ... underrelaxation factor for F(I,J,NF)
c RHO(I,J) .... density at the grid point
c RHOCON ...... constant reference density--RHOREF*TREF
c RHOREF ...... reference density
c RMN(J) ...... value of the radius r at the YV(J) interface
c SIGMA ....... neutron activation cross section for the parent
c                nuclide
c SMAX ........ the largest absolute value of the mass source in the
c                pressure-correction equation
c SSUM ........ algebraic sum of all the mass sources in the
c                pressure-correction equation
c SX(J) ....... scale factor for the x direction at grid
c                locations Y(J)
c SXMN(J) ..... scale factor for the x direction at interface
c                locations YV(J)
c T(I,J) ...... absolute temperature at the grid point
c TIME ........ time for unsteady problems
c TIN ......... initial temperature of the fluid
c TITLE(NF) ... title of a variable
c TREF ........ reference temperature to calculate the density of the
c                fluid
c TVOSO(I) .... total volumetric source in each station
c U(I,J) ...... velocity in the x direction
c UIN ......... initial u velocity of the fluid
c V(I,J) ...... velocity in the y direction
c VOSO(I,J) ... volumetric source in the control volume
c X(I) ........ value of x at the grid location I
c XCV(I) ...... width of the main control volume in the x direction
c XCVI(I) ..... the part of XCV(I) that overlaps on the control volume
c                for U(I,J)
c XCVIP(I) .... the part of XCV(I) that overlaps on the control volume
c                for U(I+1,J)
c XCVS(I) ..... width of the control volume for U(I,J) in the
c                x direction
c XDIF(I) ..... the difference X(I)-X(I-1)
c XDIST(I) .... distance in the x direction for a point in the FINDER
c                algorithm (subroutine FINDER)
c XL .......... length of the calculation domain in the x direction
c XL1...XLn ... lengths of the different regions of the calculation
c                domain in the x direction
c XMU(I,J) .... mean velocity in the control volume
c XND ......... radionuclide concentration transferred from the lower
c                control volume
c XNDACT(I,J) . final radionuclide concentration in the control volume
c XNDPRE(I,J) . previous radionuclide concentration in the control
c                volume
c XNI ......... initial radionuclide concentration in the control
c                volume
c XNL ......... radionuclide concentration transferred from the left
c                control volume
```

```
c XNU ......... radionuclide concentration transferred from the upper
c               control volume
c XPHI(I,J) ... neutron flux in the control volume
c XPRE(I,J) ... relative pressure
c XRHO(I,J) ... density of the fluid
c XTIME(I,J) .. time spent by a unit volume of the fluid inside the
c               the control volume
c XTIME1(I,J) . time spent by a unit volume of the fluid to reach the
c               end of a control volume, starting from the entrance of
c               the pipe, travelling in the same row of control
c               volumes, with recirculating fluid and time-dependent
c               activation
c XTIME2(J) ... time spent by a unit volume of the fluid to reach the
c               exit of the pipe, starting from the entrance of the
c               pipe, travelling in the same row of control volumes,
c               with recirculating fluid and time-dependent activation
c XTIME3(I,J) . time spent by a unit volume of the fluid to reach the
c               end of a control volume, starting from the entrance of
c               the pipe, travelling in the same row of control volumes,
c               and without recirculating fluid
c XTIME4(J) ... time spent by a unit volume of the fluid to reach the
c               exit of the pipe, starting from the entrance of the
c               pipe, travelling in the same row of control volumes,
c               and without recirculating fluid
c XU(I) ....... value of x at the interface of the control volume in
c               the x direction--location of U(I,J)
c Y(J) ........ value of y at the grid location J
c YCV(J) ...... width of the main control volume in the y direction
c YCVR(J) ..... area of the main control volume parallel to the
c               y direction
c YCVRS(J) .... area of the control volume for V(I,J) parallel to the
c               y direction
c YCVS(J) ..... width of the control volume for V(I,J) in the
c               y direction
c YDIF(J) ..... the difference Y(J)-Y(J-1)
c YDIST(I) .... distance in the y direction for a point in the FINDER
c               algorithm (subroutine FINDER)
c YL .......... length of the calculation domain in the y direction
c YV(J) ....... value of y at the interface of the control volume in
c               the y direction--location of V(I,J)
c
C*************************************************************************C
    1 FORMAT(1X,68(1H*),//,
     +15X,40HOUTPUT FROM THE COMPUTER PROGRAM RNATPA1,/,
     +24X,21HUNIVERSITY OF FLORIDA,/,
     +14X,42HDEPARTMENT OF NUCLEAR ENGINEERING SCIENCES,/,
     +26X,17HS. Gavazza - 1992,/)
    2 FORMAT(1X,68(1H*),//,10X,A50,//,1X,68(1H*),/)
      CALL BEGIN1
      IF(LSTART.OR.LSTACT) GO TO 15
      NEND=6+NFILES
      DO 10 IUNIT=6,NEND
      WRITE(IUNIT,1)
   10 WRITE(IUNIT,2) HEAD
   15 CALL SETUP1
      CALL BEGIN2
   20 CALL DENSE
      CALL BOUND
      CALL OUTPU1
      IF(LSTOP.OR.LSTACT) THEN
      CALL ACTRA
      STOP
```

```
      ENDIF
      CALL SETUP2
      GO TO 20
      END
C*********************************************************************C
```

Subroutine FFLOW

```
C*********************************************************************C
      SUBROUTINE FFLOW
C*********************************************************************C
$INCLUDE:'INVAR.FOR'
C*********************************************************************C
    1 FORMAT(15X,'COMPUTATION FOR AXISYMMETRIC GEOMETRY ',/)
    2 FORMAT(1X,68(1H*),/)
C=====================================================================C
      ENTRY SETUP1
C=====================================================================C
      L1=ID
      M1=JD
      L2=L1-1
      L3=L2-1
      M2=M1-1
      M3=M2-1
      IF(LGRID) THEN
      CALL GRID
      GO TO 12
      ENDIF
      R(1)=0.0
      XU(2)=0.0
      DX=XL/FLOAT(L1-2)
      DO 5 I=3,L1
    5 XU(I)=XU(I-1)+DX
      YV(2)=0.0
      DY=YL/FLOAT(M1-2)
      DO 6 J=3,M1
    6 YV(J)=YV(J-1)+DY
      X(1)=XU(2)
      DO 10 I=2,L2
   10 X(I)=0.5*(XU(I+1)+XU(I))
      X(L1)=XU(L1)
      Y(1)=YV(2)
      DO 11 J=2,M2
   11 Y(J)=0.5*(YV(J+1)+YV(J))
      Y(M1)=YV(M1)
   12 DO 15 I=2,L1
   15 XDIF(I)=X(I)-X(I-1)
      DO 18 I=2,L2
   18 XCV(I)=XU(I+1)-XU(I)
      DO 20 I=3,L2
   20 XCVS(I)=XDIF(I)
      XCVS(3)=XCVS(3)+XDIF(2)
      XCVS(L2)=XCVS(L2)+XDIF(L1)
      DO 22 I=3,L3
      XCVI(I)=0.5*XCV(I)
   22 XCVIP(I)=XCVI(I)
      XCVIP(2)=XCV(2)
      XCVI(L2)=XCV(L2)
      DO 35 J=2,M1
```

```
35 YDIF(J)=Y(J)-Y(J-1)
   DO 40 J=2,M2
40 YCV(J)=YV(J+1)-YV(J)
   DO 45 J=3,M2
45 YCVS(J)=YDIF(J)
   YCVS(3)=YCVS(3)+YDIF(2)
   YCVS(M2)=YCVS(M2)+YDIF(M1)
55 DO 50 J=2,M1
50 R(J)=R(J-1)+YDIF(J)
   RMN(2)=R(1)
   DO 60 J=3,M2
60 RMN(J)=RMN(J-1)+YCV(J-1)
   RMN(M1)=R(M1)
   DO 57 J=1,M1
   SX(J)=1.0
   SXMN(J)=1.0
57 CONTINUE
   DO 62 J=2,M2
   YCVR(J)=R(J)*YCV(J)
   ARX(J)=YCVR(J)
62 CONTINUE
   DO 64 J=4,M3
64 YCVRS(J)=(0.5*(R(J)+R(J-1)))*YDIF(J)
   YCVRS(3)=(0.5*(R(3)+R(1)))*YCVS(3)
   YCVRS(M2)=(0.5*(R(M1)+R(M3)))*YCVS(M2)
   DO 65 J=3,M3
   ARXJ(J)=0.25*(1.0+RMN(J)/R(J))*ARX(J)
65 ARXJP(J)=ARX(J)-ARXJ(J)
   ARXJP(2)=ARX(2)
   ARXJ(M2)=ARX(M2)
   DO 70 J=3,M3
   FV(J)=ARXJP(J)/ARX(J)
70 FVP(J)=1.0-FV(J)
   DO 85 I=3,L2
   FX(I)=0.5*XCV(I-1)/XDIF(I)
85 FXM(I)=1.0-FX(I)
   FX(2)=0.0
   FXM(2)=1.0
   FX(L1)=1.0
   FXM(L1)=0.0
   DO 90 J=3,M2
   FY(J)=0.5*YCV(J-1)/YDIF(J)
90 FYM(J)=1.0-FY(J)
   FY(2)=0.0
   FYM(2)=1.0
   FY(M1)=1.0
   FYM(M1)=0.0
   RHOCON=RHOREF*TREF
   DO 92 J=1,M1
   DO 92 I=1,L1
   PC(I,J)=0.0
   U(I,J)=0.0
   V(I,J)=0.0
   CON(I,J)=0.0
   AP(I,J)=0.0
   RHO(I,J)=RHOCON
   P(I,J)=0.0
92 CONTINUE
   IF(LSTART.OR.LSTACT) RETURN
   NEND=6+NFILES
   DO 95 IUNIT=6,NEND
   WRITE(IUNIT,1)
```

```
   95 WRITE(IUNIT,2)
      RETURN
C=======================================================================C
      ENTRY DENSE
C=======================================================================C
      IF(LSTACT) RETURN
      RHOCON=RHOREF*TREF
      DO J=1,M1
      DO I=1,L1
      RHO(I,J)=RHOCON/T(I,J)
      END DO
      END DO
      RETURN
C=======================================================================C
      ENTRY BOUND
C=======================================================================C
      IF(LSTACT) RETURN
C.....U-VELOCITY
      Y1=Y(2)-Y(1)
      Y2=Y(3)-Y(2)
      DO I=2,L1
      U1=U(I,2)-U(I,3)
      SLO=U1/Y2
      U(I,1)=U(I,2)+SLO*Y1
      END DO
C.....INFLOW AND OUTFLOW
      FLOWIN=0.0
      DO J=2,M2
      FLOWIN=FLOWIN+RHO(1,J)*U(2,J)*ARX(J)
      END DO
      DO J=2,M2
      U(L1,J)=U(L2,J)*(FX(L2)*RHO(L2,J)+FXM(L2)*RHO(L1,J))/
     +RHO(L1,J)
      END DO
      FL=0.0
      ARS=0.0
      UMIN=0.0
      DO J=2,M2
      AR=RHO(L1,J)*ARX(J)
      ARS=ARS+AR
      FL=FL+AR*U(L1,J)
      IF(U(L1,J).LT.0.0) UMIN=AMAX1(UMIN,-U(L1,J))
      END DO
      FACTOR=FLOWIN/(FL+ARS*UMIN+1.0E-30)
      DO J=2,M2
      U(L1,J)=(U(L1,J)+UMIN)*FACTOR
      END DO
      FLOWOU=0.0
      DO J=2,M2
      FLOWOU=FLOWOU+U(L1,J)*RHO(L1,J)*ARX(J)
      END DO
      PAI=3.141593
      FLOWIN=2.0*PAI*FLOWIN
      FLOWOU=2.0*PAI*FLOWOU
C.....V-VELOCITY
      X1=X(L1)-X(L2)
      X2=X(L2)-X(L2-1)
      DO J=2,M1
      V1=V(L2,J)-V(L2-1,J)
      SLO=V1/X2
      V(L1,J)=V(L2,J)+SLO*X1
      END DO
```

```
C.....TEMPERATURE
      DO I=1,L1
      T1=T(I,2)-T(I,3)
      SLO=T1/Y2
      T(I,1)=T(I,2)+SLO*Y1
      END DO
      DO J=1,M1
      T1=T(L2,J)-T(L2-1,J)
      SLO=T1/X2
      T(L1,J)=T(L2,J)+SLO*X1
      END DO
      RETURN
C=====================================================================C
      ENTRY SETUP2
C=====================================================================C
C.... COEFFICIENTS FOR THE U EQUATION
      NF=1
      IF(.NOT.LSOLVE(NF)) GO TO 100
      IST=3
      JST=2
      IF(LGASOR(NF)) THEN
      CALL GASOR
      GO TO 101
      ENDIF
      DO J=1,M1
      DO I=1,L1
      GAM(I,J)=AMU
      END DO
      END DO
      DO I=1,L1
      GAM(I,1)=0.0
      END DO
      DO J=2,M1
      GAM(L1,J)=0.0
      END DO
  101 REL=1.0-RELAX(NF)
      DO 102 I=3,L2
      FL=XCVI(I)*V(I,2)*RHO(I,1)
      FLM=XCVIP(I-1)*V(I-1,2)*RHO(I-1,1)
      FLOW=R(1)*(FL+FLM)
      DIFF=R(1)*(XCVI(I)*GAM(I,1)+XCVIP(I-1)*GAM(I-1,1))/YDIF(2)
      CALL DIFLOW
  102 AJM(I,2)=ACOF+AMAX1(0.0,FLOW)
      DO 103 J=2,M2
      FLOW=ARX(J)*U(2,J)*RHO(1,J)
      DIFF=ARX(J)*GAM(1,J)/(XCV(2)*SX(J))
      CALL DIFLOW
      AIM(3,J)=ACOF+AMAX1(0.0,FLOW)
      DO 103 I=3,L2
      IF(I.EQ.L2) GO TO 104
      FL=U(I,J)*(FX(I)*RHO(I,J)+FXM(I)*RHO(I-1,J))
      FLP=U(I+1,J)*(FX(I+1)*RHO(I+1,J)+FXM(I+1)*RHO(I,J))
      FLOW=ARX(J)*0.5*(FL+FLP)
      DIFF=ARX(J)*GAM(I,J)/(XCV(I)*SX(J))
      GO TO 105
  104 FLOW=ARX(J)*U(L1,J)*RHO(L1,J)
      DIFF=ARX(J)*GAM(L1,J)/(XCV(L2)*SX(J))
  105 CALL DIFLOW
      AIM(I+1,J)=ACOF+AMAX1(0.0,FLOW)
      AIP(I,J)=AIM(I+1,J)-FLOW
      IF(J.EQ.M2) GO TO 106
      FL=XCVI(I)*V(I,J+1)*(FY(J+1)*RHO(I,J+1)+FYM(J+1)*RHO(I,J))
```

```
      FLM=XCVIP(I-1)*V(I-1,J+1)*(FY(J+1)*RHO(I-1,J+1)+FYM(J+1)*
     +RHO(I-1,J))
      GM=GAM(I,J)*GAM(I,J+1)/(YCV(J)*GAM(I,J+1)+YCV(J+1)*GAM(I,J)+
     +1.0E-30)*XCVI(I)
      GMM=GAM(I-1,J)*GAM(I-1,J+1)/(YCV(J)*GAM(I-1,J+1)+YCV(J+1)*
     +GAM(I-1,J)+1.0E-30)*XCVIP(I-1)
      DIFF=RMN(J+1)*2.0*(GM+GMM)
      GO TO 107
  106 FL=XCVI(I)*V(I,M1)*RHO(I,M1)
      FLM=XCVIP(I-1)*V(I-1,M1)*RHO(I-1,M1)
      DIFF=R(M1)*(XCVI(I)*GAM(I,M1)+XCVIP(I-1)*GAM(I-1,M1))/YDIF(M1)
  107 FLOW=RMN(J+1)*(FL+FLM)
      CALL DIFLOW
      AJM(I,J+1)=ACOF+AMAX1(0.0,FLOW)
      AJP(I,J)=AJM(I,J+1)-FLOW
      VOL=YCVR(J)*XCVS(I)
      APT=(RHO(I,J)*XCVI(I)+RHO(I-1,J)*XCVIP(I-1))/(XCVS(I)*DT)
      AP(I,J)=AP(I,J)-APT
      CON(I,J)=CON(I,J)+APT*U(I,J)
      AP(I,J)=(-AP(I,J)*VOL+AIP(I,J)+AIM(I,J)+AJP(I,J)+AJM(I,J))/
     +RELAX(NF)
      CON(I,J)=CON(I,J)*VOL+REL*AP(I,J)*U(I,J)
      DU(I,J)=VOL/(XDIF(I)*SX(J))
      CON(I,J)=CON(I,J)+DU(I,J)*(P(I-1,J)-P(I,J))
      DU(I,J)=DU(I,J)/AP(I,J)
  103 CONTINUE
      CALL SOLVE
  100 CONTINUE
C.....COEFFICIENTS FOR THE V EQUATION
      NF=2
      IF(.NOT.LSOLVE(NF)) GO TO 200
      IST=2
      JST=3
      IF(LGASOR(NF)) THEN
      CALL GASOR
      GO TO 211
      ENDIF
      DO J=2,M2
      DO I=2,L2
      AP(I,J)=-AMU/(R(J)**2.0)
      END DO
      END DO
  211 REL=1.0-RELAX(NF)
      DO 202 I=2,L2
      AREA=R(1)*XCV(I)
      FLOW=AREA*V(I,2)*RHO(I,1)
      DIFF=AREA*GAM(I,1)/YCV(2)
      CALL DIFLOW
  202 AJM(I,3)=ACOF+AMAX1(0.0,FLOW)
      DO 203 J=3,M2
      FL=ARXJ(J)*U(2,J)*RHO(1,J)
      FLM=ARXJP(J-1)*U(2,J-1)*RHO(1,J-1)
      FLOW=FL+FLM
      DIFF=(ARXJ(J)*GAM(1,J)+ARXJP(J-1)*GAM(1,J-1))/(XDIF(2)*SXMN(J))
      CALL DIFLOW
      AIM(2,J)=ACOF+AMAX1(0.0,FLOW)
      DO 203 I=2,L2
      IF(I.EQ.L2) GO TO 204
      FL=ARXJ(J)*U(I+1,J)*(FX(I+1)*RHO(I+1,J)+FXM(I+1)*RHO(I,J))
      FLM=ARXJP(J-1)*U(I+1,J-1)*(FX(I+1)*RHO(I+1,J-1)+FXM(I+1)*
     +RHO(I,J-1))
      GM=GAM(I,J)*GAM(I+1,J)/(XCV(I)*GAM(I+1,J)+XCV(I+1)*GAM(I,J)+
```

```
     +1.0E-30)*ARXJ(J)
      GMM=GAM(I,J-1)*GAM(I+1,J-1)/(XCV(I)*GAM(I+1,J-1)+XCV(I+1)*
     +GAM(I,J-1)+1.0E-30)*ARXJP(J-1)
      DIFF=2.0*(GM+GMM)/SXMN(J)
      GO TO 205
  204 FL=ARXJ(J)*U(L1,J)*RHO(L1,J)
      FLM=ARXJP(J-1)*U(L1,J-1)*RHO(L1,J-1)
      DIFF=(ARXJ(J)*GAM(L1,J)+ARXJP(J-1)*GAM(L1,J-1))/
     +(XDIF(L1)*SXMN(J))
  205 FLOW=FL+FLM
      CALL DIFLOW
      AIM(I+1,J)=ACOF+AMAX1(0.0,FLOW)
      AIP(I,J)=AIM(I+1,J)-FLOW
      IF(J.EQ.M2) GO TO 206
      AREA=R(J)*XCV(I)
      FL=V(I,J)*(FY(J)*RHO(I,J)+FYM(J)*RHO(I,J-1))*RMN(J)
      FLP=V(I,J+1)*(FY(J+1)*RHO(I,J+1)+FYM(J+1)*RHO(I,J))*RMN(J+1)
      FLOW=(FV(J)*FL+FVP(J)*FLP)*XCV(I)
      DIFF=AREA*GAM(I,J)/YCV(J)
      GO TO 207
  206 AREA=R(M1)*XCV(I)
      FLOW=AREA*V(I,M1)*RHO(I,M1)
      DIFF=AREA*GAM(I,M1)/YCV(M2)
  207 CALL DIFLOW
      AJM(I,J+1)=ACOF+AMAX1(0.0,FLOW)
      AJP(I,J)=AJM(I,J+1)-FLOW
      VOL=YCVRS(J)*XCV(I)
      SXT=SX(J)
      IF(J.EQ.M2) SXT=SX(M1)
      SXB=SX(J-1)
      IF(J.EQ.3) SXB=SX(1)
      APT=(ARXJ(J)*RHO(I,J)*0.5*(SXT+SXMN(J))+ARXJP(J-1)*RHO(I,J-1)*
     +0.5*(SXB+SXMN(J)))/(YCVRS(J)*DT)
      AP(I,J)=AP(I,J)-APT
      CON(I,J)=CON(I,J)+APT*V(I,J)
      AP(I,J)=(-AP(I,J)*VOL+AIP(I,J)+AIM(I,J)+AJP(I,J)+AJM(I,J))/
     +RELAX(NF)
      CON(I,J)=CON(I,J)*VOL+REL*AP(I,J)*V(I,J)
      DV(I,J)=VOL/YDIF(J)
      CON(I,J)=CON(I,J)+DV(I,J)*(P(I,J-1)-P(I,J))
      DV(I,J)=DV(I,J)/AP(I,J)
  203 CONTINUE
      CALL SOLVE
  200 CONTINUE
C.....COEFFICIENTS FOR THE PRESSURE CORRECTION EQUATION
      NF=3
      IF(.NOT.LSOLVE(NF)) GO TO 500
      IST=2
      JST=2
      IF(LGASOR(3)) CALL GASOR
      SMAX=0.0
      SSUM=0.0
      DO 410 J=2,M2
      DO 410 I=2,L2
      VOL=YCVR(J)*XCV(I)
  410 CON(I,J)=CON(I,J)*VOL
      DO 402 I=2,L2
      ARHO=R(1)*XCV(I)*RHO(I,1)
      CON(I,2)=CON(I,2)+ARHO*V(I,2)
  402 AJM(I,2)=0.0
      DO 403 J=2,M2
      ARHO=ARX(J)*RHO(1,J)
```

```
      CON(2,J)=CON(2,J)+ARHO*U(2,J)
      AIM(2,J)=0.0
      DO 403 I=2,L2
      IF(I.EQ.L2) GO TO 404
      ARHO=ARX(J)*(FX(I+1)*RHO(I+1,J)+FXM(I+1)*RHO(I,J))
      FLOW=ARHO*U(I+1,J)
      CON(I,J)=CON(I,J)-FLOW
      CON(I+1,J)=CON(I+1,J)+FLOW
      AIP(I,J)=ARHO*DU(I+1,J)
      AIM(I+1,J)=AIP(I,J)
      GO TO 405
  404 ARHO=ARX(J)*RHO(L1,J)
      CON(I,J)=CON(I,J)-ARHO*U(L1,J)
      AIP(I,J)=0.0
  405 IF(J.EQ.M2) GO TO 406
      ARHO=RMN(J+1)*XCV(I)*(FY(J+1)*RHO(I,J+1)+FYM(J+1)*RHO(I,J))
      FLOW=ARHO*V(I,J+1)
      CON(I,J)=CON(I,J)-FLOW
      CON(I,J+1)=CON(I,J+1)+FLOW
      AJP(I,J)=ARHO*DV(I,J+1)
      AJM(I,J+1)=AJP(I,J)
      GO TO 407
  406 ARHO=RMN(M1)*XCV(I)*RHO(I,M1)
      CON(I,J)=CON(I,J)-ARHO*V(I,M1)
      AJP(I,J)=0.0
  407 AP(I,J)=AIP(I,J)+AIM(I,J)+AJP(I,J)+AJM(I,J)
      PC(I,J)=0.0
      SMAX=AMAX1(SMAX,ABS(CON(I,J)))
      SSUM=SSUM+CON(I,J)
  403 CONTINUE
      CALL SOLVE
C.....CORRECTION FOR PRESSURE AND VELOCITIES
      NF=4
      DO 501 J=2,M2
      DO 501 I=2,L2
      P(I,J)=P(I,J)+PC(I,J)*RELAX(NF)
      IF(I.NE.2) U(I,J)=U(I,J)+DU(I,J)*(PC(I-1,J)-PC(I,J))
      IF(J.NE.2) V(I,J)=V(I,J)+DV(I,J)*(PC(I,J-1)-PC(I,J))
  501 CONTINUE
  500 CONTINUE
C.....COEFFICIENTS FOR OTHER EQUATIONS
      IF(NFD.LT.5) GO TO 599
      IST=2
      JST=2
      DO 600 N=5,NFD
      NF=N
      IF(.NOT.LSOLVE(NF)) GO TO 600
      IF(NF.EQ.5) THEN
      IF(LGASOR(5)) THEN
      CALL GASOR
      GO TO 601
      ENDIF
      AMUT=AK/ACP
      DO J=1,M1
      DO I=1,L1
      GAM(I,J)=AMUT
      END DO
      END DO
      DO I=1,L1
      GAM(I,1)=0.0
      END DO
      DO J=2,M2
```

```
      GAM(L1,J)=0.0
      END DO
      ENDIF
      IF(LGASOR(NF)) CALL GASOR
  601 REL=1.0-RELAX(NF)
      DO 602 I=2,L2
      AREA=R(1)*XCV(I)
      FLOW=AREA*V(I,2)*RHO(I,1)
      DIFF=AREA*GAM(I,1)/YDIF(2)
      CALL DIFLOW
  602 AJM(I,2)=ACOF+AMAX1(0.0,FLOW)
      DO 603 J=2,M2
      FLOW=ARX(J)*U(2,J)*RHO(1,J)
      DIFF=ARX(J)*GAM(1,J)/(XDIF(2)*SX(J))
      CALL DIFLOW
      AIM(2,J)=ACOF+AMAX1(0.0,FLOW)
      DO 603 I=2,L2
      IF(I.EQ.L2) GO TO 604
      FLOW=ARX(J)*U(I+1,J)*(FX(I+1)*RHO(I+1,J)+FXM(I+1)*RHO(I,J))
      DIFF=ARX(J)*2.0*GAM(I,J)*GAM(I+1,J)/((XCV(I)*GAM(I+1,J)+
     +XCV(I+1)*GAM(I,J)+1.0E-30)*SX(J))
      GO TO 605
  604 FLOW=ARX(J)*U(L1,J)*RHO(L1,J)
      DIFF=ARX(J)*GAM(L1,J)/(XDIF(L1)*SX(J))
  605 CALL DIFLOW
      AIM(I+1,J)=ACOF+AMAX1(0.0,FLOW)
      AIP(I,J)=AIM(I+1,J)-FLOW
      AREA=RMN(J+1)*XCV(I)
      IF(J.EQ.M2) GO TO 606
      FLOW=AREA*V(I,J+1)*(FY(J+1)*RHO(I,J+1)+FYM(J+1)*RHO(I,J))
      DIFF=AREA*2.0*GAM(I,J)*GAM(I,J+1)/(YCV(J)*GAM(I,J+1)+
     +YCV(J+1)*GAM(I,J)+1.0E-30)
      GO TO 607
  606 FLOW=AREA*V(I,M1)*RHO(I,M1)
      DIFF=AREA*GAM(I,M1)/YDIF(M1)
  607 CALL DIFLOW
      AJM(I,J+1)=ACOF+AMAX1(0.0,FLOW)
      AJP(I,J)=AJM(I,J+1)-FLOW
      VOL=YCVR(J)*XCV(I)
      APT=RHO(I,J)/DT
      AP(I,J)=AP(I,J)-APT
      CON(I,J)=CON(I,J)+APT*F(I,J,NF)
      AP(I,J)=(-AP(I,J)*VOL+AIP(I,J)+AIM(I,J)+AJP(I,J)+AJM(I,J))/
     +RELAX(NF)
      CON(I,J)=CON(I,J)*VOL+REL*AP(I,J)*F(I,J,NF)
  603 CONTINUE
      CALL SOLVE
  600 CONTINUE
  599 CONTINUE
      TIME=TIME+DT
      ITER=ITER+1
      IF(ITER.GE.LAST) LSTOP=.TRUE.
      RETURN
      END
C*********************************************************************C
```

Subroutine ALGOR

```
C*********************************************************************C
```

```
      SUBROUTINE ALGOR
C*********************************************************************C
$INCLUDE:'INVAR.FOR'
C*********************************************************************C
C=====================================================================C
      ENTRY DIFLOW
C=====================================================================C
      ACOF=DIFF
      IF(FLOW.EQ.0.0) RETURN
      TEMP=DIFF-ABS(FLOW)*0.1
      ACOF=0.0
      IF(TEMP.LE.0.0) RETURN
      TEMP=TEMP/DIFF
      ACOF=DIFF*TEMP**5
      RETURN
C=====================================================================C
      ENTRY SOLVE
C=====================================================================C
      ISTF=IST-1
      JSTF=JST-1
      IT1=L2+IST
      IT2=L3+IST
      JT1=M2+JST
      JT2=M3+JST
      DO 999 NT=1,NTIMES(NF)
      N=NF
      IF(.NOT.LBLK(NF)) GO TO 10
      PT(ISTF)=0.0
      QT(ISTF)=0.0
      DO 11 I=IST,L2
      BL=0.0
      BLP=0.0
      BLM=0.0
      BLC=0.0
      DO 12 J=JST,M2
      BL=BL+AP(I,J)
      IF(J.NE.M2) BL=BL-AJP(I,J)
      IF(J.NE.JST) BL=BL-AJM(I,J)
      BLP=BLP+AIP(I,J)
      BLM=BLM+AIM(I,J)
      BLC=BLC+CON(I,J)+AIP(I,J)*F(I+1,J,N)+AIM(I,J)*F(I-1,J,N)
     ++AJP(I,J)*F(I,J+1,N)+AJM(I,J)*F(I,J-1,N)-AP(I,J)*F(I,J,N)
   12 CONTINUE
      DENOM=BL-PT(I-1)*BLM
      IF(ABS(DENOM/BL).LT.1.0E-10) DENOM=1.0E30
      PT(I)=BLP/DENOM
      QT(I)=(BLC+BLM*QT(I-1))/DENOM
   11 CONTINUE
      BL=0.0
      DO 13 II=IST,L2
      I=IT1-II
      BL=BL*PT(I)+QT(I)
      DO 13 J=JST,M2
   13 F(I,J,N)=F(I,J,N)+BL
      PT(JSTF)=0.0
      QT(JSTF)=0.0
      DO 21 J=JST,M2
      BL=0.0
      BLP=0.0
      BLM=0.0
      BLC=0.0
      DO 22 I=IST,L2
```

```
      BL=BL+AP(I,J)
      IF(I.NE.L2) BL=BL-AIP(I,J)
      IF(I.NE.IST) BL=BL-AIM(I,J)
      BLP=BLP+AJP(I,J)
      BLM=BLM+AJM(I,J)
      BLC=BLC+CON(I,J)+AIP(I,J)*F(I+1,J,N)+AIM(I,J)*F(I-1,J,N)
     ++AJP(I,J)*F(I,J+1,N)+AJM(I,J)*F(I,J-1,N)-AP(I,J)*F(I,J,N)
   22 CONTINUE
      DENOM=BL-PT(J-1)*BLM
      IF(ABS(DENOM/BL).LT.1.0E-10) DENOM=1.0E30
      PT(J)=BLP/DENOM
      QT(J)=(BLC+BLM*QT(J-1))/DENOM
   21 CONTINUE
      BL=0.0
      DO 23 JJ=JST,M2
      J=JT1-JJ
      BL=BL*PT(J)+QT(J)
      DO 23 I=IST,L2
   23 F(I,J,N)=F(I,J,N)+BL
   10 CONTINUE
      DO 90 J=JST,M2
      PT(ISTF)=0.0
      QT(ISTF)=F(ISTF,J,N)
      DO 70 I=IST,L2
      DENOM=AP(I,J)-PT(I-1)*AIM(I,J)
      PT(I)=AIP(I,J)/DENOM
      TEMP=CON(I,J)+AJP(I,J)*F(I,J+1,N)+AJM(I,J)*F(I,J-1,N)
      QT(I)=(TEMP+AIM(I,J)*QT(I-1))/DENOM
   70 CONTINUE
      DO 80 II=IST,L2
      I=IT1-II
   80 F(I,J,N)=F(I+1,J,N)*PT(I)+QT(I)
   90 CONTINUE
      DO 190 JJ=JST,M3
      J=JT2-JJ
      PT(ISTF)=0.0
      QT(ISTF)=F(ISTF,J,N)
      DO 170 I=IST,L2
      DENOM=AP(I,J)-PT(I-1)*AIM(I,J)
      PT(I)=AIP(I,J)/DENOM
      TEMP=CON(I,J)+AJP(I,J)*F(I,J+1,N)+AJM(I,J)*F(I,J-1,N)
      QT(I)=(TEMP+AIM(I,J)*QT(I-1))/DENOM
  170 CONTINUE
      DO 180 II=IST,L2
      I=IT1-II
  180 F(I,J,N)=F(I+1,J,N)*PT(I)+QT(I)
  190 CONTINUE
      DO 290 I=IST,L2
      PT(JSTF)=0.0
      QT(JSTF)=F(I,JSTF,N)
      DO 270 J=JST,M2
      DENOM=AP(I,J)-PT(J-1)*AJM(I,J)
      PT(J)=AJP(I,J)/DENOM
      TEMP=CON(I,J)+AIP(I,J)*F(I+1,J,N)+AIM(I,J)*F(I-1,J,N)
      QT(J)=(TEMP+AJM(I,J)*QT(J-1))/DENOM
  270 CONTINUE
      DO 280 JJ=JST,M2
      J=JT1-JJ
  280 F(I,J,N)=F(I,J+1,N)*PT(J)+QT(J)
  290 CONTINUE
      DO 390 II=IST,L3
      I=IT2-II
```

```
      PT(JSTF)=0.0
      QT(JSTF)=F(I,JSTF,N)
      DO 370 J=JST,M2
      DENOM=AP(I,J)-PT(J-1)*AJM(I,J)
      PT(J)=AJP(I,J)/DENOM
      TEMP=CON(I,J)+AIP(I,J)*F(I+1,J,N)+AIM(I,J)*F(I-1,J,N)
      QT(J)=(TEMP+AJM(I,J)*QT(J-1))/DENOM
  370 CONTINUE
      DO 380 JJ=JST,M2
      J=JT1-JJ
  380 F(I,J,N)=F(I,J+1,N)*PT(J)+QT(J)
  390 CONTINUE
  999 CONTINUE
      DO 400 J=2,M2
      DO 400 I=2,L2
      CON(I,J)=0.0
      AP(I,J)=0.0
  400 CONTINUE
      RETURN
      END
C*********************************************************************C
```

Subroutine ACTRA

```
C*********************************************************************C
      SUBROUTINE ACTRA
C*********************************************************************C
$INCLUDE:'INVAR.FOR'
C*********************************************************************C
      IF(LSTACT) THEN
      OPEN(10,FILE='TEMPFILE.222')
      READ(10,*)((U(I,J),J=1,M1),I=1,L1)
      READ(10,*)((V(I,J),J=1,M1),I=1,L1)
      READ(10,*)((PC(I,J),J=1,M1),I=1,L1)
      READ(10,*)((XPRE(I,J),J=1,M1),I=1,L1)
      READ(10,*)((T(I,J),J=1,M1),I=1,L1)
      READ(10,*)((XRHO(I,J),J=1,M1),I=1,L1)
      READ(10,*)((RHO(I,J),J=1,M1),I=1,L1)
      CLOSE(10)
      GO TO 85
      ENDIF
      IF(ICRIT.EQ.0) RETURN
   85 CONTINUE
C.....COUPLING EQUATIONS
C.....Mean velocity--XMU(I,J)--for each control volume
      DO J=1,M1
      XMU(1,J)=U(2,J)
      XMU(L1,J)=U(L1,J)
      END DO
      DO I=2,L2
      DO J=1,M1
      XMU(I,J)=U(I,J)+(U(I+1,J)-U(I,J))*(X(I)-XU(I))/
     +(XU(I+1)-XU(I))
      END DO
      END DO
C.....Mass flow rate--FMFR(I,J)--for each control volume
      DO I=1,L1
      DO J=1,M1
      FMFR(I,J)=RHO(I,J)*ARX(J)*XMU(I,J)
```

```
      END DO
      END DO
C.....Mass flow rate--FMFR(I,1)--for each station
      DO I=1,L1
      FMFR(I,1)=0.0
      DO J=1,M1
      FMFR(I,1)=FMFR(I,1)+FMFR(I,J)
      END DO
      END DO
C.....Correction factor--CF--for the mass flow rate
      DO I=2,L1
      DIF=FMFR(I,1)-FMFR(1,1)
      DO J=2,M2
      CF=(FMFR(I,J)*DIF)/FMFR(I,1)
      FMFR(I,J)=FMFR(I,J)-CF
C.....Correction of the mean velocity--XMU(I,J)--for each
C.....control volume
      XMU(I,J)=FMFR(I,J)/(RHO(I,J)*ARX(J))
      END DO
      END DO
C.....Mass flow rate transferred to or from the control volume
C.....--FTACV(I,J)
      DO I=1,L1
      FTACV(I,1)=0.0
      FTACV(I,M1)=0.0
      END DO
      DO J=1,M1
      FTACV(1,J)=0.0
      FTACV(L1,J)=0.0
      END DO
      DO I=2,L2
      DO J=2,M2
      JJ=M1-J+1
      FTACV(I,JJ)=FMFR(I+1,JJ)-FMFR(I,JJ)+FTACV(I,JJ+1)
      END DO
      END DO
C.....Time spent inside a control volume--XTIME(I,J)
      DO I=1,L1
      XTIME(I,1)=0.0
      XTIME(I,M1)=0.0
      END DO
      DO J=2,M2
      XTIME(1,J)=0.0
      XTIME(L1,J)=0.0
      END DO
      DO I=2,L2
      DO J=2,M2
      XTIME(I,J)=XCV(I)/XMU(I,J)
      END DO
      END DO
C.....RADIOACTIVATION EQUATIONS
C.....SPACE- AND CYCLE-DEPENDENT ACTIVATION
C.....Radionuclide concentrations in the boundaries
C.....(entrance, center line, and wall of the pipe)
C.....--XNDACT(1,J),XNDACT(I,1), and XNDACT(I,M1)
      IF(.NOT.LCYCLE) GO TO 350
      IF(LSTART) IFLAG1=1
      DO N=1,NCYCLE
      NCYC=N
      IF(NCYCLE.EQ.1) GO TO 150
      SUM=0.0
      AR=0.0
```

```
      DO J=1,M1
      SUM=SUM+XNDACT(L1,J)*ARX(J)
      AR=AR+ARX(J)
      END DO
      DO J=1,M1
      XNDACT(1,J)=SUM/AR
      END DO
  150 DO I=1,L1
      XNDACT(I,1)=0.0
      XNDACT(I,M1)=0.0
      END DO
      BLAMB=1.0/ALAMB
      DO I=2,L1
      DO J=2,M2
      JJ=M1-J+1
C.....Radionuclide concentrations transferred from other
C.....control volumes--XNU, XND, and XNL
      IF(I.EQ.2) THEN
      XNU=0.0
      XND=0.0
      GO TO 100
      ENDIF
C.....Radionuclide concentration transferred from the
C.....upper control volume--XNU
      IF(JJ.EQ.M2) THEN
      XNU=0.0
      GO TO 200
      ENDIF
      IF(FTACV(I-1,JJ+1).GT.0.0) THEN
      FT=FTACV(I-1,JJ+1)/FMFR(I-1,JJ)
      IF(FT.GT.1.0) FT=1.0
      XNU=-FT*XNDACT(I-1,JJ)
      ENDIF
      IF(FTACV(I-1,JJ+1).EQ.0.0) THEN
      XNU=0.0
      ENDIF
      IF(FTACV(I-1,JJ+1).LT.0.0) THEN
      FT=FTACV(I-1,JJ+1)/FMFR(I-1,JJ+1)
      IF(FT.LT.-1.0) FT=-1.0
      XNU=-FT*XNDACT(I-1,JJ+1)
      ENDIF
  200 CONTINUE
C.....Radionuclide concentration transferred from the
C.....lower control volume--XND
      IF(JJ.EQ.2) THEN
      XND=0.0
      GO TO 100
      ENDIF
      IF(FTACV(I-1,JJ).GT.0.0) THEN
      FT=FTACV(I-1,JJ)/FMFR(I-1,JJ-1)
      IF(FT.GT.1.0) FT=1.0
      XND=FT*XNDACT(I-1,JJ-1)
      ENDIF
      IF(FTACV(I-1,JJ).EQ.0.0) THEN
      XND=0.0
      ENDIF
      IF(FTACV(I-1,JJ).LT.0.0) THEN
      FT=FTACV(I-1,JJ)/FMFR(I-1,JJ)
      IF(FT.LT.-1.0) FT=-1.0
      XND=FT*XNDACT(I-1,JJ)
      ENDIF
  100 CONTINUE
```

```
C.....Radionuclide concentration transferred from the
C.....left control volume--XNL
      XNL=XNDACT(I-1,JJ)
C.....Initial radionuclide concentration in the control
C.....volume--XNI
      XNI=XNL+XNU+XND
C.....Final radionuclide concentration in the control
C.....volume--XNDACT(I,J)
      XND=FRA*XRHO(I,JJ)
      XT1=-ALAMB*XTIME(I,JJ)
      XT2=EXP(XT1)
      XT3=BLAMB*XPHI(I,JJ)*XND*SIGMA*(1.0-XT2)
      XT4=XNI*XT2
      XNDACT(I,JJ)=XT3+XT4
      END DO
      END DO
C.....VOLUMETRIC SOURCE EQUATIONS
C.....Volumetric source for each control volume--VOSO(I,J)
      DO I=1,L1
      DO J=1,M1
      VOSO(I,J)=ALAMB*XNDACT(I,J)
      END DO
      END DO
C.....Total volumetric source for each station--TVOSO(I)
      DO I=1,L1
      SUM=0.0
      AR=0.0
      DO J=1,M1
      SUM=SUM+VOSO(I,J)*ARX(J)
      AR=AR+ARX(J)
      END DO
      TVOSO(I)=SUM/AR
      END DO
C.....Production rate of radionuclide in each control volume
C.....--PRORA(I,J)
      DO I=1,L1
      DO J=1,M1
      PRORA(I,J)=FRA*XRHO(I,J)*SIGMA*XPHI(I,J)
      END DO
      END DO
C.....PRINT OUT THE VALUES OF THE VARIABLES
      IF(MOD(NCYC,JUMPC).NE.0) GO TO 345
      NEND=6+NFILES
      IF(LFINDV) THEN
      DO NIND=1,NFDP
      IF(LPRINT(NIND)) GO TO 59
      END DO
      GO TO 62
      ENDIF
   59 CONTINUE
      DO IUNIT=6,NEND
      WRITE(IUNIT,60)NCYC
   60 FORMAT(/,1X,18HNUMBER OF CYCLES =,I6,3X,41(1H*))
      END DO
   62 CONTINUE
      CALL XPRINT
      IF(LWRITE) GO TO 340
      IFLAG1=1
C.....Print out the total volumetric source
      IF(LPRINT(15))THEN
   10 FORMAT(1X,15(1H*),1X,A36,1X,15(1H*))
   20 FORMAT(1X,4H I =,I6,6I9)
```

```
   30 FORMAT(6X,1P7E9.2)
   40 FORMAT(1H )
   50 FORMAT(1X,//)
      NEND=6+NFILES
      DO IUNIT=6,NEND
      WRITE(IUNIT,50)
      WRITE(IUNIT,10) TITLE(15)
      WRITE(IUNIT,10) TITLE(16)
      WRITE(IUNIT,40)
      END DO
      IFST=1
      IBEG=IFST-7
  300 CONTINUE
      IBEG=IBEG+7
      IEND=IBEG+6
      IEND=MIN0(IEND,L1)
      DO IUNIT=6,NEND
      WRITE(IUNIT,20)(I,I=IBEG,IEND)
      WRITE(IUNIT,30)(TVOSO(I),I=IBEG,IEND)
      WRITE(IUNIT,40)
      END DO
      IF(IEND.LT.L1) GO TO 300
      ENDIF
  340 CONTINUE
      IF(LWRITE) CALL WRITER
      IFLAG1=1
      IF(LFINDV) THEN
      IF(LCYCLE.AND.LATIME) THEN
      LATIME=.FALSE.
      CALL FINDER
      LATIME=.TRUE.
      ENDIF
      IF(LCYCLE.AND..NOT.LATIME) THEN
      CALL FINDER
      ENDIF
      ENDIF
  345 CONTINUE
      END DO
  350 CONTINUE
C.....SPACE- AND TIME-DEPENDENT ACTIVATION
C.....Time controller variables for the activation time of
C.....each control volume and each row of control volumes
C.....--XTIME1(I,J), XTIME2(J), XTIME3(I,J), and XTIME4(J)
      IF(.NOT.LATIME) GO TO 670
      DO J=2,M2
      DO I=1,L1
      SUM=0.0
      DO II=1,I
      SUM=SUM+XTIME(II,J)
      END DO
      XTIME1(I,J)=SUM
      XTIME3(I,J)=XTIME1(I,J)
      END DO
      XTIME2(J)=XTIME1(L1,J)
      XTIME4(J)=XTIME2(J)
      END DO
C.....Radionuclide concentrations in the control volumes
C.....--XNDACT(I,J) and XNDPRE(I,J)
      DO J=1,M1
      DO I=1,L1
      XNDACT(I,J)=XNDTEM(I,J)
      XNDPRE(I,J)=XNDTEM(I,J)
```

```
      END DO
      END DO
      IFLAG1=0
      ATIME=ATI
      ICOUNT=0
      DO J=2,M2
      NN(J)=1
      END DO
  650 CONTINUE
      IF(ATIME.GE.ATF) ATIME=ATF
C.....Radionuclide concentrations in the boundaries
C.....(center line and wall of the pipe)
C.....--XNDACT(I,1) and XNDACT(I,M1)
      DO I=1,L1
      XNDACT(I,1)=0.0
      XNDACT(I,M1)=0.0
      END DO
      BLAMB=1.0/ALAMB
      DO I=2,L1
      DO J=2,M2
      JJ=M1-J+1
C.....Radionuclide concentrations transferred from other
C.....control volumes--XNU, XND, and XNL
      IF(ATIME.LT.XTIME1(I,JJ)) THEN
      XNDACT(I,JJ)=XNDPRE(I,JJ)
      GO TO 520
      ENDIF
      IF(ATIME.GE.XTIME1(I,JJ)) THEN
      IF(I.EQ.2) THEN
      XNU=0.0
      XND=0.0
      GO TO 400
      ENDIF
C.....Radionuclide concentration transferred from the
C.....upper control volume--XNU
      IF(JJ.EQ.M2) THEN
      XNU=0.0
      GO TO 500
      ENDIF
      IF(FTACV(I-1,JJ+1).GT.0.0) THEN
      FT=FTACV(I-1,JJ+1)/FMFR(I-1,JJ)
      IF(FT.GT.1.0) FT=1.0
      XNU=-FT*XNDPRE(I-1,JJ)
      ENDIF
      IF(FTACV(I-1,JJ+1).EQ.0.0) THEN
      XNU=0.0
      ENDIF
      IF(FTACV(I-1,JJ+1).LT.0.0) THEN
      FT=FTACV(I-1,JJ+1)/FMFR(I-1,JJ+1)
      IF(FT.LT.-1.0) FT=-1.0
      XNU=-FT*XNDPRE(I-1,JJ+1)
      ENDIF
  500 CONTINUE
C.....Radionuclide concentration transferred from the
C.....lower control volume--XND
      IF(JJ.EQ.2) THEN
      XND=0.0
      GO TO 400
      ENDIF
      IF(FTACV(I-1,JJ).GT.0.0) THEN
      FT=FTACV(I-1,JJ)/FMFR(I-1,JJ-1)
      IF(FT.GT.1.0) FT=1.0
```

```
      XND=FT*XNDPRE(I-1,JJ-1)
      ENDIF
      IF(FTACV(I-1,JJ).EQ.0.0) THEN
      XND=0.0
      ENDIF
      IF(FTACV(I-1,JJ).LT.0.0) THEN
      FT=FTACV(I-1,JJ)/FMFR(I-1,JJ)
      IF(FT.LT.-1.0) FT=-1.0
      XND=FT*XNDPRE(I-1,JJ)
      ENDIF
  400 CONTINUE
C.....Radionuclide concentration transferred from the
C.....left control volume--XNL
      XNL=XNDPRE(I-1,JJ)
C.....Initial radionuclide concentration in the control
C.....volume--XNI
      XNI=XNL+XNU+XND
C.....Final radionuclide concentration in the control
C.....volume--XNDACT(I,J) and XNDPRE(I,J)
      XT=ATIME-XTIME1(I-1,JJ)
      IF(ATIME.GE.XTIME1(I,JJ)) XT=XTIME(I,JJ)
      XND=FRA*XRHO(I,JJ)
      XT1=-ALAMB*XT
      XT2=EXP(XT1)
      XT3=BLAMB*XPHI(I,JJ)*XND*SIGMA*(1.0-XT2)
      XT4=XNI*XT2
      XNDACT(I,JJ)=XT3+XT4
      IF(XT.EQ.XTIME(I,JJ)) XNDPRE(I,JJ)=XNDACT(I,JJ)
      ENDIF
  520 CONTINUE
      END DO
      END DO
C.....Updating of the time controller variables in function
C.....of the activation time--XTIME1(I,J) and XTIME2(J)
      IF(LATREC) THEN
      DO J=2,M2
      IF(ATIME.GT.XTIME2(J)) THEN
      NN(J)=NN(J)+1
      XTIME2(J)=NN(J)*XTIME4(J)
      DO I=1,L1
      XTIME1(I,J)=(NN(J)-1)*XTIME4(J)+XTIME3(I,J)
      END DO
      ENDIF
      END DO
C.....Radionuclide concentration in the boundary
C.....(entrance of the pipe)--XNDACT(1,J) and XNDPRE(1,J)
      SUM=0.0
      AR=0.0
      DO J=1,M1
      SUM=SUM+XNDPRE(L1,J)*ARX(J)
      AR=AR+ARX(J)
      END DO
      DO J=2,M2
      XNDACT(1,J)=SUM/AR
      XNDPRE(1,J)=XNDACT(1,J)
      END DO
      ENDIF
C.....VOLUMETRIC SOURCE EQUATIONS
C.....Volumetric source for each control volume--VOSO(I,J)
      DO I=1,L1
      DO J=1,M1
      VOSO(I,J)=ALAMB*XNDACT(I,J)
```

```
      END DO
      END DO
C.....Total volumetric source for each station--TVOSO(I)
      DO I=1,L1
      SUM=0.0
      AR=0.0
      DO J=1,M1
      SUM=SUM+VOSO(I,J)*ARX(J)
      AR=AR+ARX(J)
      END DO
      TVOSO(I)=SUM/AR
      END DO
C.....Production rate of radionuclide in each control volume
C.....--PRORA(I,J)
      DO I=1,L1
      DO J=1,M1
      PRORA(I,J)=FRA*XRHO(I,J)*SIGMA*XPHI(I,J)
      END DO
      END DO
C.....PRINT OUT THE VALUES OF THE VARIABLES
      IF(ATF.GT.0.0.AND.ATIME.EQ.0.0) GO TO 600
      IF (MOD(ICOUNT,JUMPT).NE.0) GO TO 600
      NEND=6+NFILES
      IF(LFINDV) THEN
      DO NIND=1,NFDP
      IF(LPRINT(NIND)) GO TO 63
      END DO
      GO TO 64
      ENDIF
   63 CONTINUE
      DO IUNIT=6,NEND
      WRITE(IUNIT,61) ATIME
   61 FORMAT(/,1X,17HACTIVATION TIME =,1PE11.4,1Hs,3X,36(1H*))
      END DO
   64 CONTINUE
      CALL XPRINT
      IF(LWRITE) THEN
      CALL WRITER
      IFLAG1=1
      GO TO 590
      ENDIF
      IFLAG1=1
C.....Print out the total volumetric source
      IF(LPRINT(15))THEN
   11 FORMAT(1X,15(1H*),1X,A36,1X,15(1H*))
   21 FORMAT(1X,4H I =,I6,6I9)
   31 FORMAT(6X,1P7E9.2)
   41 FORMAT(1H )
   51 FORMAT(1X,//)
      NEND=6+NFILES
      DO IUNIT=6,NEND
      WRITE(IUNIT,51)
      WRITE(IUNIT,11) TITLE(15)
      WRITE(IUNIT,11) TITLE(16)
      WRITE(IUNIT,41)
      END DO
      IFST=1
      IBEG=IFST-7
  550 CONTINUE
      IBEG=IBEG+7
      IEND=IBEG+6
      IEND=MIN0(IEND,L1)
```

```
      DO IUNIT=6,NEND
      WRITE(IUNIT,21)(I,I=IBEG,IEND)
      WRITE(IUNIT,31)(TVOSO(I),I=IBEG,IEND)
      WRITE(IUNIT,41)
      END DO
      IF(IEND.LT.L1) GO TO 550
      ENDIF
  590 CONTINUE
      IF(LFINDV) THEN
      IF(LCYCLE.AND.LATIME) THEN
      LCYCLE=.FALSE.
      CALL FINDER
      LCYCLE=.TRUE.
      ENDIF
      IF(.NOT.LCYCLE.AND.LATIME) THEN
      CALL FINDER
      ENDIF
      ENDIF
  600 CONTINUE
      IF(ATIME.EQ.ATF) GO TO 670
      ICOUNT=ICOUNT+1
      ATIME=ATI+ICOUNT*DAT
      GO TO 650
  670 CONTINUE
C.....COUPLING FILES
      OPEN(7,FILE='GEOMETRY.INP')
      WRITE(7,*)(X(I),I=1,ID),(Y(J),J=1,JD),(XCV(I),I=1,ID),
     +          (ARX(J),J=1,JD)
      CLOSE(7)
      OPEN(7,FILE='VSOURCES.INP')
      WRITE(7,*)((VOSO(I,J),J=1,JD),I=1,ID)
      CLOSE(7)
      RETURN
      END
C*********************************************************************C
```

Subroutine PRINTER

```
C*********************************************************************C
      SUBROUTINE PRINTER
C*********************************************************************C
$INCLUDE:'INVAR.FOR'
C*********************************************************************C
    5 FORMAT(1X,68(1H*),//,1X,A64,//,1X,68(1H*))
   10 FORMAT(/,1X,15(1H*),1X,A36,1X,15(1H*))
   20 FORMAT(1X,4H I =,I6,6I9)
   25 FORMAT(1X,4H J =,I6,6I9)
   30 FORMAT(1X,1HJ)
   35 FORMAT(1X,1HI)
   40 FORMAT(1X,I3,2X,1P7E9.2)
   50 FORMAT(1H )
   51 FORMAT(1X,4H I =,2X,7(I4,5X))
   52 FORMAT(1X,4H X =,1P7E9.2)
   54 FORMAT(1X,4H J =,2X,7(I4,5X))
   55 FORMAT(1X,4H Y =,1P7E9.2)
   60 FORMAT(5X,1HI,11X,1HX,10X,2HXU)
   70 FORMAT(5X,1HJ,11X,1HY,10X,2HYV)
   80 FORMAT(1X,I5,2X,F10.5,2X,F10.5)
   85 FORMAT(/,5X,1HI,11X,1HX,7X,5HTVOSO,/)
```

```
   90 FORMAT(1X,I5,2X,F10.5,3X,1PE9.2)
   91 FORMAT(//,1X,A36,/)
   92 FORMAT(1X,'POS',I1,4X,'X=',F8.4,'m',4X,'Y=',F8.4,'m')
   93 FORMAT(/,1X,'NCYCLE',4X,'POS',I1,8X,'POS',I1,8X,'POS',I1,8X,
     +'POS',I1,8X,'POS',I1)
   94 FORMAT(/,1X,'ATIME(s)',2X,'POS',I1,8X,'POS',I1,8X,'POS',I1,8X,
     +'POS',I1,8X,'POS',I1)
   95 FORMAT(1X,I6,2X,5(1X,1PE11.4))
   96 FORMAT(1X,F8.1,5(1X,1PE11.4))
   97 FORMAT(/,1X,A36)
   98 FORMAT(1X,'NCYCLE',4X,'POS',I1,8X,'POS',I1,8X,'POS',I1,8X,
     +'POS',I1,8X,'POS',I1)
   99 FORMAT(1X,'ATIME(s)',2X,'POS',I1,8X,'POS',I1,8X,'POS',I1,8X,
     +'POS',I1,8X,'POS',I1)
  704 FORMAT(1X,5HNCVX=,I4,2X,5HNCVY=,I4,2X,5HNCVT=,I5,2X,
     +'NUMBER OF CYCLES=',I11,/,35X,'ACTIVATION TIME =',
     +1PE11.4,' s',/)
  705 FORMAT(1X,'IU =',I5,2X,'JU =',I5,2X,'IT =',I5,2X,'JT =',I5,/)
  710 FORMAT(1X,'ITER',6X,'SMAX',6X,'SSUM',2X,'U(IU,JU)',2X,'T(IT,JT)'
     +,4X,'FLOWIN',3X,'FLOWOUT')
  755 FORMAT(1X,I4,1P6E10.3)
  765 FORMAT(/,1X,'ITER=',I5,7X,
     +'RATIO=ABS(U(ITER)-U(ITER-1)/U(ITER))=',F10.6,/)
C=======================================================================C
      ENTRY OUTPU1
C=======================================================================C
      NEND=6+NFILES
      IF(LSTART) GO TO 720
      IF(ITER.EQ.0) THEN
      N1=ID-2
      N2=JD-2
      N1N2=N1*N2
      DO IUNIT=6,NEND
      WRITE(IUNIT,704) N1,N2,N1N2,NCYCLE,ATF
      IF(LSTACT) RETURN
      WRITE(IUNIT,705) IU,JU,IT,JT
      WRITE(IUNIT,710)
      END DO
      ENDIF
  720 CONTINUE
      IF(ITER.EQ.0) THEN
      TEMPU=U(IU,JU)
      TEMPR=1.0
      ICOUNT=0
      ICRIT=0
      ENDIF
      IF(ITER.NE.0) THEN
      RATIO=ABS((U(IU,JU)-TEMPU)/U(IU,JU))
      IF(RATIO.LE.TEMPR) THEN
      TEMPR=RATIO
      ICOUNT=ITER
      ENDIF
      TEMPU=U(IU,JU)
      IF(RATIO.LE.CRIT) THEN
      LAST=ITER
      ICRIT=1
      LSTOP=.TRUE.
      GO TO 745
      ENDIF
      ENDIF
      IF(ITER.EQ.LAST) GO TO 745
      IF(MOD(ITER,JUMP).NE.0) GO TO 730
```

```
  745 DO IUNIT=6,NEND
      WRITE(IUNIT,755) ITER,SMAX,SSUM,U(IU,JU),T(IT,JT),FLOWIN,FLOWOU
      END DO
C.....Temporary files to restart the calculation
      OPEN(9,FILE='TEMPFILE.111')
      WRITE(9,*)((U(I,J),J=1,M1),I=1,L1)
      WRITE(9,*)((V(I,J),J=1,M1),I=1,L1)
      WRITE(9,*)((T(I,J),J=1,M1),I=1,L1)
      WRITE(9,*)((RHO(I,J),J=1,M1),I=1,L1)
      WRITE(9,*)((PC(I,J),J=1,M1),I=1,L1)
      WRITE(9,*)((P(I,J),J=1,M1),I=1,L1)
      CLOSE(9)
  730 IF(ITER.NE.LAST) RETURN
      DO IUNIT=6,NEND
      WRITE(IUNIT,765)ICOUNT,RATIO
      END DO
C.....Densities to be printed out--XRHO(I,J)
      DO J=1,M1
      DO I=1,L1
      XRHO(I,J)=RHO(I,J)
      END DO
      END DO
      RETURN
C=====================================================================C
      ENTRY XPRINT
C=====================================================================C
C.....Stream function calculation--F(I,J,3)
      IF(.NOT.LPRINT(3)) GO TO 280
      F(2,2,3)=0.0
      DO I=2,L1
      IF(I.NE.2) F(I,2,3)=F(I-1,2,3)-RHO(I-1,1)*V(I-1,2)*R(1)*XCV(I-1)
      DO J=3,M1
      RHOM=FX(I)*RHO(I,J-1)+FXM(I)*RHO(I-1,J-1)
      F(I,J,3)=F(I,J-1,3)+RHOM*U(I,J-1)*ARX(J-1)
      END DO
      END DO
  280 CONTINUE
      IF(.NOT.LPRINT(4)) GO TO 290
C.....Boundary pressures and pressure field--P(I,J) and XPRE(I,J)
      DO J=2,M2
      P(1,J)=(P(2,J)*XCVS(3)-P(3,J)*XDIF(2))/XDIF(3)
      P(L1,J)=(P(L2,J)*XCVS(L2)-P(L3,J)*XDIF(L1))/XDIF(L2)
      END DO
      DO I=2,L2
      P(I,1)=(P(I,2)*YCVS(3)-P(I,3)*YDIF(2))/YDIF(3)
      P(I,M1)=(P(I,M2)*YCVS(M2)-P(I,M3)*YDIF(M1))/YDIF(M2)
      END DO
      P(1,1)=P(2,1)+P(1,2)-P(2,2)
      P(L1,1)=P(L2,1)+P(L1,2)-P(L2,2)
      P(1,M1)=P(2,M1)+P(1,M2)-P(2,M2)
      P(L1,M1)=P(L2,M1)+P(L1,M2)-P(L2,M2)
      PREF=P(IPREF,JPREF)
      DO J=1,M1
      DO I=1,L1
      P(I,J)=P(I,J)-PREF
      XPRE(I,J)=P(I,J)
      END DO
      END DO
  290 CONTINUE
C.....Prints out the geometrical dimensions
C.....--X(I), and Y(J)
      IF(LWRITE) GO TO 398
```

```
      IF(IFLAG1.EQ.1) GO TO 320
      NEND=6+NFILES
      DO IUNIT=6,NEND
      WRITE(IUNIT,50)
      END DO
      IEND=0
  301 IF(IEND.EQ.L1) GO TO 310
      IBEG=IEND+1
      IEND=IEND+7
      IEND=MIN0(IEND,L1)
      DO IUNIT=6,NEND
      WRITE(IUNIT,50)
      WRITE(IUNIT,51)(I,I=IBEG,IEND)
      END DO
      DO IUNIT=6,NEND
      WRITE(IUNIT,52)(X(I),I=IBEG,IEND)
      END DO
      GO TO 301
  310 JEND=0
      DO IUNIT=6,NEND
      WRITE(IUNIT,50)
      END DO
  311 IF(JEND.EQ.M1) GO TO 320
      JBEG=JEND+1
      JEND=JEND+7
      JEND=MIN0(JEND,M1)
      DO IUNIT=6,NEND
      WRITE(IUNIT,50)
      WRITE(IUNIT,54)(J,J=JBEG,JEND)
      WRITE(IUNIT,55)(Y(J),J=JBEG,JEND)
      END DO
      GO TO 311
  320 CONTINUE
C.....Prints out the values of the variables--F(I,J,NFD)
      DO 399 N=1,NFD
      NF=N
      IF(.NOT.LPRINT(NF)) GO TO 399
      DO IUNIT=6,NEND
      WRITE(IUNIT,50)
      WRITE(IUNIT,10)TITLE(NF)
      END DO
      IFST=1
      JFST=1
      IF(NF.EQ.1.OR.NF.EQ.3) IFST=2
      IF(NF.EQ.2.OR.NF.EQ.3) JFST=2
      IBEG=IFST-7
  110 CONTINUE
      IBEG=IBEG+7
      IEND=IBEG+6
      IEND=MIN0(IEND,L1)
      DO IUNIT=6,NEND
      WRITE(IUNIT,50)
      WRITE(IUNIT,20)(I,I=IBEG,IEND)
      WRITE(IUNIT,30)
      END DO
      JFL=JFST+M1
      DO 115 JJ=JFST,M1
      J=JFL-JJ
      DO IUNIT=6,NEND
      WRITE(IUNIT,40)J,(F(I,J,NF),I=IBEG,IEND)
      END DO
  115 CONTINUE
```

```
      IF(IEND.LT.L1) GO TO 110
  399 CONTINUE
  398 CONTINUE
C.....Temporary files to restart the calculation
      OPEN(10,FILE='TEMPFILE.222')
      WRITE(10,*) ((U(I,J),J=1,M1),I=1,L1)
      WRITE(10,*) ((V(I,J),J=1,M1),I=1,L1)
      WRITE(10,*) ((PC(I,J),J=1,M1),I=1,L1)
      WRITE(10,*) ((XPRE(I,J),J=1,M1),I=1,L1)
      WRITE(10,*) ((T(I,J),J=1,M1),I=1,L1)
      WRITE(10,*) ((XRHO(I,J),J=1,M1),I=1,L1)
      WRITE(10,*) ((RHO(I,J),J=1,M1),I=1,L1)
      CLOSE(10)
      RETURN
C=====================================================================C
      ENTRY WRITER
C=====================================================================C
C.....Prints out the geometrical dimensions
C.....--X(I), XU(I), Y(J), and YV(J)
      NEND=6+NFILES
      DO IUNIT=6,NEND
      IF(LSTACT.OR.IFLAG1.EQ.1) GO TO 100
      WRITE(IUNIT,50)
      WRITE(IUNIT,60)
      WRITE(IUNIT,50)
      DO I=1,L1
      IF(I.EQ.1) WRITE(IUNIT,80)I,X(I)
      IF(I.GT.1) WRITE (IUNIT,80)I,X(I),XU(I)
      END DO
      WRITE(IUNIT,50)
      WRITE(IUNIT,70)
      WRITE(IUNIT,50)
      DO J=1,M1
      IF(J.EQ.1) WRITE(IUNIT,80)J,Y(J)
      IF(J.GT.1) WRITE(IUNIT,80)J,Y(J),YV(J)
      END DO
  100 CONTINUE
C.....Prints out the values of the variables--F(I,J,NFD)
      DO N=1,NFD
      NF=N
      IF(.NOT.LPRINT(NF)) GO TO 400
      WRITE(IUNIT,50)
      WRITE(IUNIT,10)TITLE(NF)
      IFST=1
      JFST=1
      IF(NF.EQ.1.OR.NF.EQ.3)IFST=2
      IF(NF.EQ.2.OR.NF.EQ.3)JFST=2
      JBEG=JFST-7
  500 CONTINUE
      JBEG=JBEG+7
      JEND=JBEG+6
      JEND=MIN0(JEND,M1)
      WRITE(IUNIT,50)
      WRITE(IUNIT,25)(J,J=JBEG,JEND)
      WRITE(IUNIT,35)
      DO I=IFST,L1
      WRITE(IUNIT,40)I,(F(I,J,NF),J=JBEG,JEND)
      END DO
      IF(JEND.LT.M1) GO TO 500
  400 CONTINUE
      END DO
      IF(LPRINT(15))THEN
```

```
      WRITE(IUNIT,50)
      WRITE(IUNIT,10)TITLE(15)
      WRITE(IUNIT,10)TITLE(16)
      WRITE(IUNIT,85)
      DO I=1,L1
      WRITE(IUNIT,90)I,X(I),TVOSO(I)
      END DO
      WRITE(IUNIT,50)
      WRITE(IUNIT,50)
      ENDIF
      END DO
      RETURN
C=====================================================================C
      ENTRY FINDER
C=====================================================================C
C.....Calculates and prints out the values of the
C.....chosen variables at the chosen positions
      IF(LATIME.AND.IDK.NE.1) THEN
      DO NF=5,NFD
      LFLAG2(NF)=.FALSE.
      END DO
      IDK=1
      ENDIF
      NEND=6+NFILES
      DO NF=5,NFD
      IF(LFIND(NF)) THEN
      IF(.NOT.LFLAG2(NF)) THEN
      DO IUNIT=6,NEND
      WRITE(IUNIT,91) TITLE(NF)
      DO I=1,NP
      WRITE(IUNIT,92)I,XDIST(I),YDIST(I)
      NVC(I)=I
      END DO
      LFLAG2(NF)=.TRUE.
      END DO
      ENDIF
      DO I=1,NP
      DO II=1,L2
      IF(XDIST(I).GE.X(II).AND.XDIST(I).LE.X(II+1)) THEN
      I1=II
      I2=II+1
      GO TO 150
      ENDIF
      END DO
  150 CONTINUE
      DO JJ=1,M2
      IF(YDIST(I).GE.Y(JJ).AND.YDIST(I).LE.Y(JJ+1)) THEN
      J1=JJ
      J2=JJ+1
      GO TO 200
      ENDIF
      END DO
  200 CONTINUE
      X1=X(I2)-X(I1)
      X2=XDIST(I)-X(I1)
      Y1=Y(J2)-Y(J1)
      Y2=YDIST(I)-Y(J1)
      F1=F(I1,J1,NF)+(F(I2,J1,NF)-F(I1,J1,NF))*X2/X1
      F2=F(I1,J2,NF)+(F(I2,J2,NF)-F(I1,J2,NF))*X2/X1
      F3(I)=F1+(F2-F1)*Y2/Y1
      END DO
      DO IUNIT=6,NEND
```

```
      IF(LCYCLE) THEN
      WRITE(IUNIT,97) TITLE(NF)
      WRITE(IUNIT,98)(NVC(I),I=1,NP)
      WRITE(IUNIT,95)NCYC,(F3(I),I=1,NP)
      ENDIF
      IF(LATIME) THEN
      WRITE(IUNIT,97) TITLE(NF)
      WRITE(IUNIT,99)(NVC(I),I=1,NP)
      WRITE(IUNIT,96)ATIME,(F3(I),I=1,NP)
      ENDIF
      END DO
      ENDIF
      END DO
      RETURN
      END
C*********************************************************************C
```

Subroutine ADAPT

```
C*********************************************************************C
      SUBROUTINE ADAPT
C*********************************************************************C
$INCLUDE:'INVAR.FOR'
C*********************************************************************C
C=====================================================================C
      ENTRY BEGIN1
C=====================================================================C
C
C.....DEFAULT VALUES FOR ALL VARIABLES
      DATA LSTOP/.FALSE./
      DATA LSOLVE/NFD*.FALSE./
      DATA LPRINT/NFDP*.FALSE./
C
C.....DEFAULT VALUES TO SOLVE THE GOVERNING FLUID FLOW EQUATIONS
      DATA LBLK/NFD*.TRUE./
      DATA RELAX,NTIMES/NFD*1.0,NFD*1/
      DATA TIME,DT,IPREF,JPREF/0.0,1.0E+20,1,1/
      DATA RELAX(1),RELAX(2),RELAX(5)/0.5,0.5,0.75/
      DATA LGASOR/NFD*.FALSE./
C
C.....FILES TO BE OPENED
C.....Number of files
      DATA NFILES/1/
C.....File names
      OPEN(7,FILE='N16.OUT',ACCESS='APPEND')
C.....Heading for the files
      DATA HEAD/50HN-16 VOL. RAD. SOURCES IN MOVING AIR INSIDE A PIPE/
C
C.....CHARACTERISTICS OF THE FLUID (SI Units)
C.....Initial temperature and velocity
      DATA TIN,UIN/300.0,0.3/
C.....Viscosity and temperature and density of reference
      DATA AMU,TREF,RHOREF/18.6E-6,273.0,1.293/
C.....Thermal conductivity and constant-pressure specific heat
      DATA AK,ACP/0.0262,1007.0/
C.....Neutron activation cross section, disintegration constant for
C.....the daughter radionuclide and fraction to calculate the number
C.....density of the parent nuclide
      DATA SIGMA,ALAMB,FRA/1.613E-30,0.0937,8.703E+24/
```

```
C
C.....GEOMETRY OF THE PIPE AND NUMBER OF CONTROL VOLUMES
C.....Lengths and control volumes in the longitudinal direction
      DATA XL1,XL2/3.0,9.0/
      DATA NCV1,NCV2/5,15/
C.....Length and control volumes in the radial direction
      DATA YL/0.05/
      DATA NCVY/5/
C
C.....GRID DESIGN
      DATA LGRID/.TRUE./
C
C.....VARIABLES TO BE CALCULATED AND PRINTED OUT
C.....Identifications
      DATA TITLE(1)/ 36HU Velocity in the x direction  (m/s)/
      DATA TITLE(2)/ 36HV Velocity in the y direction  (m/s)/
      DATA TITLE(3)/ 36H          Stream Function            /
      DATA TITLE(4)/ 36H         Relative Pressure           /
      DATA TITLE(5)/ 36H         Temperature   (K)           /
      DATA TITLE(6)/ 36H       Air Density    (kg/m3)       /
      DATA TITLE(7)/ 36H         CV  XMU    (m/s)            /
      DATA TITLE(8)/ 36H         CV  FMFR   (kg/s)           /
      DATA TITLE(9)/ 36H         CV  FTACV  (kg/s)           /
      DATA TITLE(10)/36H         CV  XTIME  (s)              /
      DATA TITLE(11)/36H   FAST NEUTRON FLUX   (n/(m2s))     /
      DATA TITLE(12)/36H  CV N-16  CONCENTRATION    (#/m3)   /
      DATA TITLE(13)/36H  CV N-16  VOL. SOURCE     (Bq/m3)   /
      DATA TITLE(14)/36H PRODUCTION RATE OF N-16    (#/m3)   /
      DATA TITLE(15)/36H STATION N-16  VOL. SOURCE  (Bq/m3) /
C.....Calculation and printing options
      DATA LSOLVE(1), LPRINT(1) /.TRUE., .FALSE./
      DATA LSOLVE(2), LPRINT(2) /.TRUE., .FALSE./
      DATA LSOLVE(3), LPRINT(3) /.TRUE., .FALSE./
      DATA LSOLVE(4), LPRINT(4) /.FALSE.,.FALSE./
      DATA LSOLVE(5), LPRINT(5) /.TRUE., .FALSE./
      DATA LSOLVE(6), LPRINT(6) /.FALSE.,.FALSE./
      DATA LPRINT(7), LPRINT(8) /.FALSE.,.FALSE./
      DATA LPRINT(9), LPRINT(10)/.FALSE.,.FALSE./
      DATA LPRINT(11),LPRINT(12)/.FALSE.,.FALSE./
      DATA LPRINT(13),LPRINT(14)/.TRUE. ,.FALSE./
      DATA LPRINT(15)           /.FALSE./
C
C.....ITERACTIONS PLANNED AND CONVERGENCE CRITERION
C.....Iteractions and restarting option
      DATA ITER,LAST,JUMP/0,200,10/
      DATA LSTART/.FALSE./
C.....Control volume to verify the velocity convergence
      DATA IU,JU/6,2/
C.....Control volume to verify the temperature convergence
      DATA IT,JT/6,2/
C.....Convergence criterion
      DATA CRIT/0.000001/
C
C.....ACTIVATION CALCULATION
C.....Activation as a function of number of cycles
      DATA LCYCLE/.TRUE./
      DATA NCYCLE,JUMPC/90,90/
C.....Activation as a function of space and time
      DATA LATIME,LATREC/.TRUE.,.TRUE./
      DATA ATI,ATF,DAT,JUMPT/0.0,3600.0,1.0,3600/
      DATA LSTACT/.FALSE./
C
```

```
C.....PRINTING OPTIONS
C.....Using WRITER
      DATA LWRITE/.TRUE./
C.....Using FINDER
      DATA LFINDV/.TRUE./
      DATA NP/5/
      DATA XDIST(1),YDIST(1)/ 2.0,0.045/
      DATA XDIST(2),YDIST(2)/ 4.0,0.04 /
      DATA XDIST(3),YDIST(3)/ 6.0,0.03 /
      DATA XDIST(4),YDIST(4)/ 8.0,0.02 /
      DATA XDIST(5),YDIST(5)/10.0,0.01 /
      DATA LFIND(13)/.TRUE./
      RETURN
C=====================================================================C
      ENTRY BEGIN2
C=====================================================================C
C
C.....INITIAL VALUES FOR THE VARIABLES
C.....Restarting options
      IF(LSTACT) GO TO 80
      IF(LSTART) THEN
      OPEN(9,FILE='TEMPFILE.111')
      READ(9,*)((U(I,J),J=1,M1),I=1,L1)
      READ(9,*)((V(I,J),J=1,M1),I=1,L1)
      READ(9,*)((T(I,J),J=1,M1),I=1,L1)
      READ(9,*)((RHO(I,J),J=1,M1),I=1,L1)
      READ(9,*)((PC(I,J),J=1,M1),I=1,L1)
      READ(9,*)((P(I,J),J=1,M1),I=1,L1)
      CLOSE(9)
      GO TO 80
      ENDIF
C.....Initial U velocity
      DO J=1,M1
      DO I=1,L1
      U(I,J)=UIN
      U(I,M1)=0.0
      END DO
      END DO
C.....Initial temperature of the fluid and
C.....temperature of the wall
      DO J=1,M1
      DO I=1,L1
      T(I,J)=TIN
      T(I,M1)=TIN
      END DO
      END DO
   80 CONTINUE
C.....Radiation field (Neutron flux distribution)
      DO I=1,L1
      DO J=1,M1
      IF(I.LE.NF1) XPHI(I,J)=1.0E+15
      IF(I.GT.NF1) XPHI(I,J)=0.0
      END DO
      END DO
C.....Initial radionuclide concentration
      DO I=1,L1
      DO J=1,M1
      XNDACT(I,J)=0.0
      XNDTEM(I,J)=XNDACT(I,J)
      END DO
      END DO
      RETURN
```

```
C=====================================================================C
      ENTRY GRID
C=====================================================================C
C
      R(1)=0.0
      XF1=XL1
      XF2=XF1+XL2
      NF1=NCV1+1
      NF2=NF1+NCV2+1
      DX1=XL1/FLOAT(NCV1)
      DX2=XL2/FLOAT(NCV2)
      XU(2)=0.0
      DO I=3,L1
      IF(I.LE.NF1)                XU(I)=0.0+(I-2)*DX1
      IF(I.GT.NF1.AND.I.LE.NF2) XU(I)=XF1+(I-NF1-1)*DX2
      END DO
      X(1)=XU(2)
      X(L1)=XU(L1)
      DO I=2,L2
      X(I)=0.5*(XU(I+1)+XU(I))
      END DO
      YV(2)=0.0
      IF(NCVY.EQ.1) THEN
      YV(3)=2.0E-09
      YV(4)=YL
      Y(1)=YV(2)
      Y(2)=0.5*(YV(3)+YV(2))
      Y(3)=0.5*(YV(4)+YV(3))
      Y(4)=YV(4)
      RETURN
      ENDIF
      RR=YL/(NCVY**0.5)
      DO J=3,M1
      YV(J)=((J-2)**0.5)*RR
      END DO
      Y(1)=YV(2)
      Y(M1)=YV(M1)
      DO J=2,M2
      Y(J)=0.5*(YV(J+1)+YV(J))
      END DO
      RETURN
C=====================================================================C
      ENTRY GASOR
C=====================================================================C
      RETURN
      END
C*********************************************************************C
```

Common Part INVAR.FOR

```
C*********************************************************************C
C                                                                     C
C     COMMON PART INVAR.FOR - COMPUTER PROGRAM RNATPA1                C
C                                                                     C
C*********************************************************************C
      IMPLICIT REAL*8 (A-H)
      IMPLICIT REAL*8 (O-Z)
      LOGICAL LBLK,LGASOR,LGRID,LPRINT,LSOLVE,LSTOP,LSTART,LSTACT
      LOGICAL LWRITE,LCYCLE,LATIME,LATREC,LFINDV,LFIND,LFLAG2
```

```
C=====================================================================C
      PARAMETER(         ID=22
     +,                  JD=7
     +,                  MAXIJ=22
     +,                  NFD=14
     +,                  NFDP=15                                       )
C=====================================================================C
      CHARACTER *36 TITLE
      CHARACTER *50 HEAD
      COMMON F(ID,JD,NFD),P(ID,JD),RHO(ID,JD),GAM(ID,JD),CON(ID,JD),
     +      AIP(ID,JD),AIM(ID,JD),AJP(ID,JD),AJM(ID,JD),AP(ID,JD),
     +       X(ID),XU(ID),XDIF(ID),XCV(ID),XCVS(ID),Y(JD),YV(JD),
     +       YDIF(JD),YCV(JD),YCVS(JD),YCVR(JD),YCVRS(JD),ARX(JD),
     +       ARXJ(JD),ARXJP(JD),R(JD),RMN(JD),SX(JD),SXMN(JD),
     +       XCVI(ID),XCVIP(ID),FX(ID),FXM(ID),FY(JD),FYM(JD)
      COMMON DU(ID,JD),DV(ID,JD),FV(JD),FVP(JD),XNDTEM(ID,JD),
     +       SMAX,SSUM,FLOW,DIFF,ACOF,TVOSO(ID),XNDPRE(ID,JD),
     +       XTIME1(ID,JD),XTIME3(ID,JD),XTIME2(JD),XTIME4(JD)
      COMMON /POINTS/XDIST(5),YDIST(5),F3(5)
      COMMON /DP1/BL,BLC,BLM,BLP,DENOM,PT(MAXIJ),QT(MAXIJ)
      COMMON /CNTL1/RHOREF,TREF,AMU,AK,ACP,SIGMA,ALAMB,FRA,ATI,ATF,
     +       DAT,ATIME,CRIT,TIME,DT,XL,YL,TITLE(NFD+2),RELAX(NFD),
     +       HEAD,FLOWIN,FLOWOU
      COMMON /CNTL2/NF,L1,L2,L3,M1,M2,M3,IST,JST,ITER,LAST,IPREF,
     +       JPREF,IU,JU,IT,JT,JUMP,JUMPC,JUMPT,ICRIT,NCYC,NCYCLE,
     +       IFLAG1,NFILES,NN(JD),NP,NVC(5)
      COMMON /CNTL3/LBLK(NFD),LGASOR(NFD),LPRINT(NFDP),LSOLVE(NFD),
     +       NTIMES(NFD),LSTOP,LGRID,LSTART,LSTACT,LWRITE,LCYCLE,
     +       LATIME,LFINDV,LATREC,LFIND(NFD),LFLAG2(NFD)
C=====================================================================C
      DIMENSION U(ID,JD), V(ID,JD),    PC(ID,JD),
     +          T(ID,JD), XPRE(ID,JD), XRHO(ID,JD)
      EQUIVALENCE (F(1,1,1),U(1,1)),  (F(1,1,2),V(1,1)),
     +            (F(1,1,3),PC(1,1)), (F(1,1,4),XPRE(1,1)),
     +            (F(1,1,5),T(1,1)),  (F(1,1,6),XRHO(1,1))
C=====================================================================C
      DIMENSION XMU(ID,JD), FMFR(ID,JD), FTACV(ID,JD), XTIME(ID,JD),
     +          XPHI(ID,JD), XNDACT(ID,JD), VOSO(ID,JD), PRORA(ID,JD)
      EQUIVALENCE (F(1,1,7),XMU(1,1)),   (F(1,1,8),FMFR(1,1)),
     +            (F(1,1,9),FTACV(1,1)), (F(1,1,10),XTIME(1,1)),
     +            (F(1,1,11),XPHI(1,1)), (F(1,1,12),XNDACT(1,1)),
     +            (F(1,1,13),VOSO(1,1)), (F(1,1,14),PRORA(1,1))
C*********************************************************************C
```

Output File

```
 ********************************************************************

              OUTPUT FROM THE COMPUTER PROGRAM RNATPA1
                       UNIVERSITY OF FLORIDA
                DEPARTMENT OF NUCLEAR ENGINEERING SCIENCES
                          S. Gavazza - 1992

 ********************************************************************

          N-16 VOL. RAD. SOURCES IN MOVING AIR INSIDE A PIPE

 ********************************************************************
```

COMPUTATION FOR AXISYMMETRIC GEOMETRY

****

NCVX= 20 NCVY= 5 NCVT= 100 NUMBER OF CYCLES= 90
ACTIVATION TIME = 3.6000E+03 s

IU = 6 JU = 2 IT = 6 JT = 2

ITER	SMAX	SSUM	U(IU,JU)	T(IT,JT)	FLOWIN	FLOWOUT
0	0.000E+00	0.000E+00	3.000E-01	3.000E+02	2.772E-03	2.772E-03
10	2.572E-06	3.706E-20	4.745E-01	3.000E+02	2.772E-03	2.772E-03
20	1.426E-07	-4.027E-20	4.857E-01	3.000E+02	2.772E-03	2.772E-03
30	7.192E-09	2.432E-20	4.859E-01	3.000E+02	2.772E-03	2.772E-03
32	4.873E-09	6.863E-21	4.859E-01	3.000E+02	2.772E-03	2.772E-03

ITER= 32 RATIO=ABS(U(ITER)-U(ITER-1)/U(ITER))= .000001

NUMBER OF CYCLES = 90 **********

I	X	XU
1	.00000	
2	.30000	.00000
3	.90000	.60000
4	1.50000	1.20000
5	2.10000	1.80000
6	2.70000	2.40000
7	3.30000	3.00000
8	3.90000	3.60000
9	4.50000	4.20000
10	5.10000	4.80000
11	5.70000	5.40000
12	6.30000	6.00000
13	6.90000	6.60000
14	7.50000	7.20000
15	8.10000	7.80000
16	8.70000	8.40000
17	9.30000	9.00000
18	9.90000	9.60000
19	10.50000	10.20000
20	11.10000	10.80000
21	11.70000	11.40000
22	12.00000	12.00000

J	Y	YV
1	.00000	
2	.01118	.00000
3	.02699	.02236
4	.03518	.03162
5	.04173	.03873
6	.04736	.04472
7	.05000	.05000

********** CV N-16 VOL. SOURCE (Bq/m3) **********

I \ J =	1	2	3	4	5	6	7
1	0.00E+00	8.70E+08	8.70E+08	8.70E+08	8.70E+08	8.70E+08	0.00E+00
2	0.00E+00	3.16E+09	3.26E+09	3.43E+09	3.75E+09	4.49E+09	0.00E+00

3	0.00E+00	5.42E+09	5.60E+09	5.94E+09	6.65E+09	8.06E+09	0.00E+00
4	0.00E+00	7.06E+09	7.35E+09	7.93E+09	9.35E+09	1.13E+10	0.00E+00
5	0.00E+00	8.43E+09	8.76E+09	9.49E+09	1.12E+10	1.35E+10	0.00E+00
6	0.00E+00	9.59E+09	9.91E+09	1.07E+10	1.25E+10	1.48E+10	0.00E+00
7	0.00E+00	8.83E+09	8.78E+09	9.02E+09	9.40E+09	6.36E+09	0.00E+00
8	0.00E+00	8.10E+09	7.73E+09	7.52E+09	6.94E+09	2.70E+09	0.00E+00
9	0.00E+00	7.41E+09	6.78E+09	6.24E+09	5.08E+09	1.13E+09	0.00E+00
10	0.00E+00	6.76E+09	5.93E+09	5.16E+09	3.71E+09	4.71E+08	0.00E+00
11	0.00E+00	6.16E+09	5.17E+09	4.26E+09	2.70E+09	1.94E+08	0.00E+00
12	0.00E+00	5.61E+09	4.51E+09	3.52E+09	1.97E+09	7.96E+07	0.00E+00
13	0.00E+00	5.09E+09	3.93E+09	2.90E+09	1.43E+09	3.24E+07	0.00E+00
14	0.00E+00	4.63E+09	3.42E+09	2.39E+09	1.04E+09	1.31E+07	0.00E+00
15	0.00E+00	4.20E+09	2.98E+09	1.97E+09	7.57E+08	5.31E+06	0.00E+00
16	0.00E+00	3.81E+09	2.60E+09	1.62E+09	5.50E+08	2.13E+06	0.00E+00
17	0.00E+00	3.45E+09	2.26E+09	1.33E+09	4.00E+08	8.56E+05	0.00E+00
18	0.00E+00	3.13E+09	1.97E+09	1.10E+09	2.90E+08	3.42E+05	0.00E+00
19	0.00E+00	2.84E+09	1.71E+09	9.03E+08	2.11E+08	1.37E+05	0.00E+00
20	0.00E+00	2.57E+09	1.49E+09	7.43E+08	1.53E+08	5.43E+04	0.00E+00
21	0.00E+00	2.33E+09	1.30E+09	6.12E+08	1.11E+08	2.16E+04	0.00E+00
22	0.00E+00	2.33E+09	1.30E+09	6.12E+08	1.11E+08	2.16E+04	0.00E+00

CV N-16 VOL. SOURCE (Bq/m3)

POS1	X=	2.0000m	Y=	.0450m
POS2	X=	4.0000m	Y=	.0400m
POS3	X=	6.0000m	Y=	.0300m
POS4	X=	8.0000m	Y=	.0200m
POS5	X=	10.0000m	Y=	.0100m

CV N-16 VOL. SOURCE (Bq/m3)

NCYCLE	POS1	POS2	POS3	POS4	POS5
90	1.2201E+10	6.8074E+09	4.4925E+09	3.5927E+09	2.7548E+09

ACTIVATION TIME = 3.6000E+03s **********

I	X	XU
1	.00000	
2	.30000	.00000
3	.90000	.60000
4	1.50000	1.20000
5	2.10000	1.80000
6	2.70000	2.40000
7	3.30000	3.00000
8	3.90000	3.60000
9	4.50000	4.20000
10	5.10000	4.80000
11	5.70000	5.40000
12	6.30000	6.00000
13	6.90000	6.60000
14	7.50000	7.20000
15	8.10000	7.80000
16	8.70000	8.40000
17	9.30000	9.00000
18	9.90000	9.60000
19	10.50000	10.20000
20	11.10000	10.80000
21	11.70000	11.40000
22	12.00000	12.00000

J	Y	YV

1	.00000	
2	.01118	.00000
3	.02699	.02236
4	.03518	.03162
5	.04173	.03873
6	.04736	.04472
7	.05000	.05000

********** CV N-16 VOL. SOURCE (Bq/m3) **********

I \ J =	1	2	3	4	5	6	7
1	0.00E+00	8.70E+08	8.70E+08	8.70E+08	8.70E+08	8.70E+08	0.00E+00
2	0.00E+00	3.16E+09	3.26E+09	3.43E+09	3.75E+09	4.49E+09	0.00E+00
3	0.00E+00	5.42E+09	5.60E+09	5.94E+09	6.65E+09	8.06E+09	0.00E+00
4	0.00E+00	7.06E+09	7.35E+09	7.93E+09	9.35E+09	1.13E+10	0.00E+00
5	0.00E+00	8.43E+09	8.76E+09	9.49E+09	1.12E+10	1.35E+10	0.00E+00
6	0.00E+00	9.59E+09	9.91E+09	1.07E+10	1.25E+10	1.48E+10	0.00E+00
7	0.00E+00	8.83E+09	8.78E+09	9.02E+09	9.40E+09	6.36E+09	0.00E+00
8	0.00E+00	8.10E+09	7.73E+09	7.52E+09	6.94E+09	2.70E+09	0.00E+00
9	0.00E+00	7.41E+09	6.78E+09	6.24E+09	5.08E+09	1.13E+09	0.00E+00
10	0.00E+00	6.76E+09	5.93E+09	5.16E+09	3.71E+09	4.71E+08	0.00E+00
11	0.00E+00	6.16E+09	5.17E+09	4.26E+09	2.70E+09	1.94E+08	0.00E+00
12	0.00E+00	5.61E+09	4.51E+09	3.52E+09	1.97E+09	7.96E+07	0.00E+00
13	0.00E+00	5.09E+09	3.93E+09	2.90E+09	1.43E+09	3.24E+07	0.00E+00
14	0.00E+00	4.63E+09	3.42E+09	2.39E+09	1.04E+09	1.31E+07	0.00E+00
15	0.00E+00	4.20E+09	2.98E+09	1.97E+09	7.57E+08	5.31E+06	0.00E+00
16	0.00E+00	3.81E+09	2.60E+09	1.62E+09	5.50E+08	2.13E+06	0.00E+00
17	0.00E+00	3.45E+09	2.26E+09	1.33E+09	4.00E+08	8.56E+05	0.00E+00
18	0.00E+00	3.13E+09	1.97E+09	1.10E+09	2.90E+08	3.42E+05	0.00E+00
19	0.00E+00	2.84E+09	1.71E+09	9.03E+08	2.11E+08	1.37E+05	0.00E+00
20	0.00E+00	2.57E+09	1.49E+09	7.43E+08	1.53E+08	5.43E+04	0.00E+00
21	0.00E+00	2.33E+09	1.30E+09	6.12E+08	1.11E+08	2.16E+04	0.00E+00
22	0.00E+00	2.33E+09	1.30E+09	6.12E+08	1.11E+08	2.16E+04	0.00E+00

CV N-16 VOL. SOURCE (Bq/m3)

POS1	X=	2.0000m	Y=	.0450m
POS2	X=	4.0000m	Y=	.0400m
POS3	X=	6.0000m	Y=	.0300m
POS4	X=	8.0000m	Y=	.0200m
POS5	X=	10.0000m	Y=	.0100m

CV N-16 VOL. SOURCE (Bq/m3)

ATIME(s)	POS1	POS2	POS3	POS4	POS5
3600.0	1.2201E+10	6.8074E+09	4.4925E+09	3.5927E+09	2.7548E+09

APPENDIX C
LISTING OF THE COMPUTER PROGRAM GRDOSER

A specific problem was designed to illustrate the applications of the computer programs RNATPA1 and GRDOSER. The problem and its solution using the program RNATPA1 are presented in Appendix B.

The program GRDOSER was applied to calculate the gamma ray dose equivalent rate from moving nitrogen-16 radionuclides inside the 6.0 m long pipe shielded by ordinary concrete with 0.2 m of thickness in the external loop. The coupling files GEOMETRY.INP and VSOURCES.INP generated by the RNATPA1 were used as input files for the GRDOSER.

The GEOMETRY.INP file provided the data related to the geometric dimensions X(I), Y(I), XCV(I), and ARX(J). The VSOURCES.INP file provided the data related to the volumetric radioactive sources of nitrogen-16 radionuclides after an activation time equal to 3600.0 s for the recirculating air.

The listings for the program GRDOSER, the common part INVAG.FOR, the GRDOSER.INP input file, and the GRDOSER.OUT output file are presented below. The GRDOSER comprises a program MAIN and the subroutines INPUT, OUTPUT, DOSERATE, and INTRPL. The list of Fortran variables is included in the program MAIN.

INVAG.FOR includes the COMMON and DIMENSION statements for all the important program variables. The subroutines have headings to identify the main steps of the calculations.

The GRDOSER.INP file and the common part INVAG.FOR were designed to calculate the gamma ray dose equivalent rate from moving nitrogen-16 radionuclides within the external loop of the multilayered shielded pipe at the point with coordinates x equal to 7.5 m and y equal to 1.0 m. The layers of the multilayered shield are air, iron, concrete, and air. These files also show how to incorporate the data into the program.

The files GEOMETRY.INP and VSOURCES.INP are not presented because they are written in free format and act only as coupling files.

Computer Program GRDOSER

Program MAIN

```
C*********************************************************************C
C                                                                     C
C       PROGRAM GRDOSER - GAMMA-RAY DOSE EQUIVALENT RATE FROM         C
C                         MOVING RADIONUCLIDES INSIDE A PIPE          C
C                                                                     C
C             S. Gavazza - University of Florida - 1992               C
C                                                                     C
C*********************************************************************C
      PROGRAM MAIN
C*********************************************************************C
$INCLUDE:'INVAG.FOR'
C*********************************************************************C
c
c LIST OF FORTRAN VARIABLES
c
c A(NEC,NZC) ..... parameter a for buildup calculations using
c                  Berger's formula
c A1(J,K) ........ coefficient a of the straight line y = ax + b
c                  joining the center of the control volume and the
c                  projected position of the detector in a plane
```

```
c                   that contains the center of the control volume and
c                   is perpendicular to the center line of the pipe
c ABAR ............ interpolated value for the parameter a in
c                   Berger's formula for buildup factors
c AMFP ............ mean-free-path for a shielding layer
c ARX(J) .......... area of the face of the main control volume normal
c                   to the x direction
c B1(J,K) ......... coefficient b of the straight line y = ax + b
c                   joining the center of the control volume and the
c                   projected position of the detector in a plane
c                   that contains the center of the control volume and
c                   is perpendicular to the center line of the pipe
c B(NEC,NZC) ...... parameter b for buildup calculations using
c                   Berger's formula
c BBAR ............ interpolated value for the parameter b in
c                   Berger's formula for buildup factors
c BLD ............. buildup factor for a multilayered shield
c DCVD ............ distance between the center of the control volume
c                   and the position of the detector
c DIST1(J,K,NLC) .. distance inside a layer and perpendicular to the
c                   center line of the pipe
c DIST2(J,K,NLC) .. distance inside a layer in the line of sight
c                   between the center of the control volume and the
c                   position of the detector
c DOSE(NVSC) ...... dose equivalent rate from a radioactive volumetric
c                   source
c E(NEC) .......... a gamma ray energy for buildup calculations
c ENERGY .......... energy of the gamma ray to be interpolated
c EP(NPC) ......... energy of a gamma ray in MeV
c EZERO ........... energy of a gamma ray in J
c FAC ............. factor to calculate radioactive source strengths
c FLUX ............ energy flux at the position of the detector
c GF .............. geometry factor for point-kernel calculation
c I ............... index denoting the position in the x direction
c                   --direction along the center line of the pipe
c ID .............. number of I locations allowed in array dimensions
c                   and equal to the number of control volumes in the
c                   x direction
c IFLAG1 .......... controller to indicate that a gamma ray energy
c                   cannot be interpolated in the interpolation tables
c IFLAG2 .......... controller to indicate that an effective atomic
c                   number cannot be interpolated in the interpolation
c                   tables
c INI ............. index denoting the position in the x direction of
c                   the first station within the length of the
c                   pipe to be considered
c IFIN ............ index denoting the position in the x direction of
c                   the last station within the length of the
c                   pipe to be considered
c J ............... index denoting the position in the y direction
c                   --direction of a straight line perpendicular to
c                   the center line of the pipe in the plane that
c                   contains the center line of the pipe and the
c                   position of the detector
c JD .............. number of J locations allowed in array dimensions
c                   and equal to the number of control volumes in the
c                   y direction
c K ............... index denoting an angular sector
c M1 .............. JD-1
c NCVT ............ total number of control volumes
c NCVTH ........... number of control volumes in the angular direction
c NCVX ............ number of control volumes in the x direction
```

```
c NCVY ..... number of control volumes in the y direction
c NEC ..... index denoting a energy for buildup and absorbed
c                   dose calculations
c NL ..... number of shielding layers
c NLC ..... index denoting a shielding layer
c NP ..... number of gamma rays
c NPC ..... index denoting a gamma ray
c NPF(NVSC) ..... index denoting the last gamma ray of a
c                   radioactive volumetric source
c NPI(NVSC) ..... index denoting the first gamma ray of a
c                   radioactive volumetric source
c NPS(NVSC) ..... number of gamma rays for each radioactive
c                   volumetric source
c NS ..... number of sectors in the angular direction
c NSD2 ..... NS/2
c NVS ..... number of radioactive volumetric sources
c NVSC ..... index denoting a radioactive volumetric source
c NZC ..... index denoting a effective atomic number for
c                   buildup calculations
c RL(NLC) ..... outer radius of a shielding layer
c RDET ..... distance of the detector in the y direction
c SOURCE ..... radioactive source strength
c SS ..... source strength times yield for a gamma ray
c TA ..... total attenuation provided by the multilayered
c                   shielding
c TDOSE ..... total dose equivalent rate from all radioactive
c                   volumetric sources
c THETA ..... increment in the angular direction
c TITLE1(NLC) ..... identification of a shielding layer
c TITLE2(NVSC) .... identification of a radioactive volumetric
c                   source
c TMFP ..... total mean-free-path length for a multilayered
c                   shield
c TZMFP ..... total effective atomic number times mean-free-path
c                   for a multilayered shield
c VOL ..... volume of a annular control volume
c VOSO(I,J) ..... radioactive volumetric source in a control volume
c                   of the program RNATPA1
c VOSOM(I,J,NVSC) . radioactive volumetric source in a control volume
c                   of the program GRDOSER
c X(I) ..... value of x at the grid location I corresponding
c                   to the center of a control volume
c XCV(I) ..... width of the main control volume in the
c                   x direction
c XDET ..... distance of the detector in the x direction
c XDIST1 ..... distance from the center of the control volume to
c                   the position of the detector, in the y direction
c XDIST2 ..... distance from the center of the control volume to
c                   the position of the detector, in the x direction
c XIFIN ..... distance in the x direction of the end of the
c                   length of the pipe to be considered
c XINIT ..... distance in the x direction of the beginning of
c                   the length of the pipe to be considered
c XKERN ..... point kernel
c XLAC(NPC,NLC) ... linear attenuation coefficient for a gamma ray
c                   within a shielding layer
c XME(NEC) ..... mass energy absorption coefficient in the water
c                   for a gamma ray energy
c XMUEN ..... interpolated value of the mass energy absorption
c                   coefficient for the water
c Y(J) ..... value of y at the grid location J corresponding
c                   to the center of a control volume
```

```
c YLD(NPC) ........ yield of a gamma ray
c Z(NZC) .......... an effective atomic number for builup calculations
c ZBAR ............ effective atomic number for the multilayered
c                   shield
c ZEFF(NLC) ....... effective atomic number for the shielding layer
c ZMFP ............ effective atomic number times mean-free-path for
c                   a shielding layer
C*********************************************************************C
      CALL INPUT
      CALL OUTPUT
      CALL DOSERATE
      STOP
      END
C*********************************************************************C
```

Subroutine INPUT

```
C*********************************************************************C
      SUBROUTINE INPUT
C*********************************************************************C
$INCLUDE:'INVAG.FOR'
C*********************************************************************C
C.....READS IN GRID POINT AND CONTROL VOLUME DATA
      OPEN(7,FILE='GEOMETRY.INP')
      READ(7,*)(X(I),I=1,ID),(Y(J),J=1,JD),(XCV(I),I=1,ID),
     +         (ARX(J),J=1,JD)
      CLOSE(7)
C.....READS IN VOLUMETRIC SOURCE DATA
      OPEN(7,FILE='VSOURCES.INP')
      DO NVSC=1,NVS
      READ(7,*)((VOSO(I,J),J=1,JD),I=1,ID)
      DO I=1,ID
      DO J=1,JD
      VOSOM(I,J,NVSC)=VOSO(I,J)
      END DO
      END DO
      END DO
      CLOSE(7)
C.....READS IN GRDOSER.INP FILE DATA
      OPEN(7,FILE='GRDOSER.INP')
C.....Length of the Pipe
      READ(7,*)INIT,IFIN,XINIT,XIFIN
C.....Position of the Detector
      READ(7,*)XDET,RDET
C.....Materials of the Layers
      DO NLC=1,NL
      READ(7,2)TITLE1(NLC)
    2 FORMAT(A10)
      END DO
C.....Effective Atomic Numbers and Outer Radii for the Layers
      DO NLC=1,NL
      READ(7,*)ZEFF(NLC),RL(NLC)
      END DO
C.....Identifications of the Radionuclides
      DO NVSC=1,NVS
      READ(7,3)TITLE2(NVSC)
    3 FORMAT(A12)
      END DO
C.....Number of Gamma Rays per Radionuclide
```

```
      READ(7,*)(NPS(NVSC),NVSC=1,NVS)
      DO NVSC=1,NVS
      IF(NVSC.EQ.1)THEN
      NPI(NVSC)=1
      NPF(NVSC)=NPI(NVSC)+NPS(NVSC)-1
      ENDIF
      IF(NVSC.NE.1)THEN
      NPI(NVSC)=NPF(NVSC-1)+1
      NPF(NVSC)=NPI(NVSC)+NPS(NVSC)-1
      ENDIF
      END DO
C.....Energies of the Gamma Rays
      READ(7,*)(EP(NPC),NPC=1,NP)
C.....Yields of the Gamma Rays
      READ(7,*)(YLD(NPC),NPC=1,NP)
C.....Linear Attenuation Coefficient for each Gamma Ray
C     in each Layer
      DO NPC=1,NP
      READ(7,*)(XLAC(NPC,NLC),NLC=1,NL)
      END DO
C.....Effective Atomic Numbers for Buildup Calculations
      READ(7,*)(Z(NZC),NZC=1,4)
C.....Energies and Parameters a for Buildup Calculations
C.....using Berger's Formula
      DO NEC=1,21
      READ(7,*)E(NEC),(A(NEC,NZC),NZC=1,4)
      END DO
C.....Parameters b for Buildup Calculations
C.....using Berger's Formula
      DO NEC=1,21
      READ(7,*)(B(NEC,NZC),NZC=1,4)
      END DO
C.....Mass Energy Absorption Coefficients for the Water
      READ(7,*)(XME(NEC),NEC=1,21)
      CLOSE(7)
      M1=JD-1
      NSD2=NS/2
      RETURN
      END
C*********************************************************************C
```

Subroutine OUTPUT

```
C*********************************************************************C
      SUBROUTINE OUTPUT
C*********************************************************************C
$INCLUDE:'INVAG.FOR'
C*********************************************************************C
C.....PRINTS OUT REFERENCE DATA
      OPEN(7,FILE='GRDOSER.OUT')
      DO IUNIT=6,7
      WRITE(IUNIT,30)
   30 FORMAT(1X,68(1H*),//,
     +15X,39HOUTPUT FROM THE COMPUTER PROGRAM GDOSER,/,
     +24X,21HUNIVERSITY OF FLORIDA,/,
     +14X,42HDEPARTMENT OF NUCLEAR ENGINEERING SCIENCES,/,
     +26X,17HS. Gavazza - 1992,//,
     +1X,68(1H*),//)
      WRITE(IUNIT,1)
```

```
 1 FORMAT(1X,'GAMMA RAY DOSE EQUIVALENT RATE FROM',
  +' THE',/,' MOVING RADIONUCLIDES INSIDE THE PIPE',/)
    WRITE(IUNIT,2)TITLE1(1),RL(1),XINIT,XIFIN
 2 FORMAT(1X,'FLUID AND DIMENSIONS OF THE SHIELDED PIPE',/,
  +1X,'Fluid=',1X,A10,/,1X,'Inner Radius=',1X,F7.4,'m',/,
  +1X,'Length:',2X,'XINIT=',1X,F7.4,'m',2X,'XIFIN=',1X,F7.4,'m',/)
    WRITE(IUNIT,3)XDET,RDET
 3 FORMAT(1X,'POSITION OF THE DETECTOR',/,
  +1X,'XDET=',1X,F7.4,'m',2X,'RDET=',1X,F7.4,'m',/)
    WRITE(IUNIT,4)
 4 FORMAT(1X,'MULTILAYERED SHIELD',/,1X,'Layer',2X,
  +'Material',4X,'Zeff',2X,'Outer Radius(m)')
    DO NLC=1,NL
    WRITE(IUNIT,5)NLC,TITLE1(NLC),ZEFF(NLC),RL(NLC)
 5 FORMAT(1X,I3,4X,A10,2X,F4.1,5X,F7.4)
    END DO
    WRITE(IUNIT,6)
 6 FORMAT(1H )
    WRITE(IUNIT,7)
 7 FORMAT(1X,'RADIONUCLIDE, GAMMA RAYS, ENERGIES(MeV), ',
  +'YIELDS')
    DO NVSC=1,NVS
    WRITE(IUNIT,8)TITLE2(NVSC)
 8 FORMAT(1X,A12)
    NPCI=NPI(NVSC)
    NPCF=NPF(NVSC)
    DO NPC=NPCI,NPCF
    WRITE(IUNIT,9)NPC,EP(NPC),YLD(NPC)
 9 FORMAT(1X,'GAMMA',1X,I2,':',1X,F7.4,4X,F7.4)
    END DO
    END DO
    WRITE(IUNIT,6)
    WRITE(IUNIT,10)
10 FORMAT(1X,'MATERIALS, GAMMA RAYS, LINEAR ATTEN. COEF.',
  +'(1/m)')
    DO NLC=1,NL
    WRITE(IUNIT,11)TITLE1(NLC)
11 FORMAT(1X,A10)
    DO NPC=1,NP
    WRITE(IUNIT,12)NPC,XLAC(NPC,NLC)
12 FORMAT(1X,'GAMMA',1X,I2,':',1X,F10.5)
    END DO
    END DO
    WRITE(IUNIT,6)
    IFLAG1=0
    DO NPC=1,NP
    IF(EP(NPC).LT.E(1).OR.EP(NPC).GT.E(21))THEN
    WRITE(IUNIT,13)NPC,EP(NPC)
13 FORMAT(1X,'GAMMA',1X,I2,':',1X,F7.4,'MeV',/,
  +1X,'THIS ENERGY CANNOT BE INTERPOLATED')
    IFLAG1=1
    ENDIF
    END DO
    WRITE(IUNIT,14)(Z(NZC),NZC=1,4)
14 FORMAT(1X,8HBERGER'S,' PARAMETERS FOR BUILDUP',
  +' CALCULATIONS',/,1X,'ENERGY',2X,'ZEFF VALUES',/,
  +1X,'(MeV)',3X,4(F5.1,4X))
    WRITE(IUNIT,15)
15 FORMAT(1X,'Parameter a')
    DO NEC=1,21
    WRITE(IUNIT,16)E(NEC),(A(NEC,NZC),NZC=1,4)
16 FORMAT(1X,F6.3,2X,4(F8.4,1X))
```

```
      END DO
      WRITE(IUNIT,17)
   17 FORMAT(1X,'Parameter b')
      DO NEC=1,21
      WRITE(IUNIT,18)(B(NEC,NZC),NZC=1,4)
   18 FORMAT(9X,4(F8.4,1X))
      END DO
      WRITE(IUNIT,6)
      WRITE(IUNIT,19)
   19 FORMAT(1X,'MASS ENERGY ABSORPTION COEFFICIENTES FOR',
     +' WATER',/,1X,'ENERGY',2X,'MEAC',/,1X,'(MeV)',3X,
     +'(m2/kg)')
      DO NEC=1,21
      WRITE(IUNIT,20) E(NEC),XME(NEC)
   20 FORMAT(1X,F6.3,2X,F9.5)
      END DO
      WRITE(IUNIT,6)
      END DO
      RETURN
      END
C*********************************************************************C
```

Subroutine DOSERATE

```
C*********************************************************************C
      SUBROUTINE DOSERATE
C*********************************************************************C
$INCLUDE:'INVAG.FOR'
C*********************************************************************C
C.....GEOMETRIC PARAMETER CALCULATIONS
      IF(IFLAG1.NE.0)RETURN
      PAI=3.141592654
      THETA=2.0*PAI/NS
C.....Variation in the y Direction
      DO J=2,M1
      ARC1=THETA/2.0
C.....Variation in the Angular Direction
      DO K=1,NSD2
      A1(J,K)=Y(J)*SIN(ARC1)/(RDET-Y(J)*COS(ARC1))
      B1(J,K)=A1(J,K)*RDET
      AB=A1(J,K)*B1(J,K)
      A2P1=A1(J,K)**2.0+1.0
      B2=B1(J,K)*B1(J,K)
C.....Coordinates of the GP inside the Control Volume
      D1=Y(J)*COS(ARC1)
      D2=Y(J)*SIN(ARC1)
C.....Variations in the Layers
      DO NLC=1,NL
C.....Intersections Between CV-DET Line and the Outer Radii
C.....of the Layers, Perpendicular to the CL
C.....--CV  = center of the control volume
C.....--DET = position of the detector
C.....--CL  = center line of the pipe
      D3=(AB+(A2P1*RL(NLC)**2.0-B2)**0.5)/A2P1
      D4=-A1(J,K)*D3+B1(J,K)
C.....Distances Inside the Layers, Perpendicular to the CL
      DIST1(J,K,NLC)=((D3-D1)**2.0+(D4-D2)**2.0)**0.5
      D1=D3
      D2=D4
```

```
      END DO
      ARC1=ARC1+THETA
      END DO
      END DO
C.....DOSE EQUIVALENT RATE CALCULATIONS
C.....TOTAL DOSE EQUIVALENT RATE CALCULATIONS
C.....Initializes Dose Array for each Radionuclide
      DO NVSC=1,NVS
      DOSE(NVSC)=0.0
      END DO
C.....Variation Along the x Direction
      DO I=INIT,IFIN
C.....CV-DET Distance Parallel to the CL
      IF(X(I).LE.XDET)XDIST2=XDET-X(I)
      IF(X(I).GT.XDET)XDIST2=X(I)-XDET
C.....Variation Along y Direction
      DO J=2,M1
C.....Factor for the Radioactive Source Strength Calculation
      VOL=XCV(I)*ARX(J)*2.0*PAI
      FAC=VOL/NS
C.....Variation Along the Angular Direction
      DO K=1,NSD2
C.....Distances through Layers and Distance CV-DET
      XDIST1=0.0
      DO NLC=1,NL
      XDIST1=XDIST1+DIST1(J,K,NLC)
      END DO
      ARG1=XDIST2/XDIST1
      ARC2=ATAN(ARG1)
      DCVD=0.0
      DO NLC=1,NL
      DIST2(J,K,NLC)=DIST1(J,K,NLC)/COS(ARC2)
      DCVD=DCVD+DIST2(J,K,NLC)
      END DO
C.....Geometry Factor
      GF=1.0/(4.0*PAI*DCVD**2.0)
C.....Variation of Radionuclides
      DO NVSC=1,NVS
      SOURCE=VOSOM(I,J,NVSC)*FAC
      NPCI=NPI(NVSC)
      NPCF=NPF(NVSC)
C.....Variation of Gamma Rays Energies
      DO NPC=NPCI,NPCF
C.....Total Attenuation Through the Layers and
C.....ZBAR for the Multilayered Shield
      TMFP=0.0
      TZMFP=0.0
      DO NLC=1,NL
      AMFP=XLAC(NPC,NLC)*DIST2(J,K,NLC)
      ZMFP=ZEFF(NLC)*AMFP
      TMFP=TMFP+AMFP
      TZMFP=TZMFP+ZMFP
      END DO
      TA=EXP(-TMFP)
      ZBAR=TZMFP/TMFP
      ENERGY=EP(NPC)
C.....Buildup Factor for the Multilayered Shield
C.....Mass Energy Absorption Coefficient for the Water
      CALL INTRPL
C.....Dose Equivalent Rate Calculations
      IF(IFLAG2.NE.0)RETURN
      EZERO=EP(NPC)*(1.6E-13)
```

```
      XKERN=GF*TA
      SS=SOURCE*YLD(NPC)
      FLUX=BLD*SS*XKERN*EZERO
      DOSET=FLUX*XMUEN*2.0
      DOSE(NVSC)=DOSE(NVSC)+DOSET
      END DO
      END DO
      END DO
      END DO
      END DO
C.....Total Number of Control Volumes
      NCVX=IFIN-INIT+1
      NCVY=JD-2
      NCVTH=NS
      NCVT=NCVX*NCVY*NCVTH
C.....Total Dose Equivalent Rate
      TDOSE=0.0
      DO NVSC=1,NVS
      TDOSE=TDOSE+DOSE(NVSC)
      END DO
C.....Prints out the Calculation Summaries
      DO IUNIT=6,7
      WRITE(IUNIT,1)
    1 FORMAT(1X,'CALCULATION SUMMARIES',/,1X,
     +'NUMBER OF CONTROL VOLUMES')
      WRITE(IUNIT,2)NCVX,NCVY,NCVTH,NCVT
    2 FORMAT(3X,'x Direction',5X,'=',I10,/,
     +3X,'y Direction',5X,'=',I10,/,
     +3X,'Ang. Direction',2X,'=',I10,/,
     +3X,'Total',11X,'=',I10,/)
      WRITE(IUNIT,3)
    3 FORMAT(1X,'GAMMA RAY DOSE EQUIVALENT RATE',/,
     +1X,'RADIONUCLIDE(s)',4X,'DER (Sv/s)')
      DO NVSC=1,NVS
      WRITE(IUNIT,4)TITLE2(NVSC),DOSE(NVSC)
    4 FORMAT(1X,A12,6X,1PE11.4)
      END DO
      WRITE(IUNIT,5)TDOSE
    5 FORMAT(1X,'Total',13X,1PE11.4)
      END DO
      RETURN
      END
C*********************************************************************C
```

Subroutine INTRPL

```
C*********************************************************************C
      SUBROUTINE INTRPL
C*********************************************************************C
$INCLUDE:'INVAG.FOR'
C*********************************************************************C
C.....INTERPOLATION IN ZEFF
      IFLAG2=0
      IF(ZBAR.LT.Z(1).OR.ZBAR.GT.Z(4))THEN
      DO IUNIT=6,7
      WRITE(IUNIT,1)ZBAR
    1 FORMAT(1X,'ZBAR =',1X,F4.1,/,
     +'THIS ZBAR CANNOT BE INTERPOLATED')
      END DO
```

```
      IFLAG2=1
      RETURN
      ENDIF
      DO NZC=1,3
      IF(ZBAR.GE.Z(NZC).AND.ZBAR.LE.Z(NZC+1))THEN
      K1=NZC
      K2=NZC+1
      GO TO 100
      ENDIF
      END DO
  100 CONTINUE
C.....INTERPOLATION IN ENERGY
      DO NEC=1,20
      IF(ENERGY.GE.E(NEC).AND.ENERGY.LE.E(NEC+1))THEN
      L1=NEC
      L2=NEC+1
      GO TO 200
      ENDIF
      END DO
  200 CONTINUE
C.....INTERPOLATIONS IN Z AND E FIELDS
      Z1=Z(K2)-Z(K1)
      Z2=ZBAR-Z(K1)
      E1=E(L2)-E(L1)
      E2=ENERGY-E(L1)
C.....Parameter ABAR
      AZ1=A(L1,K1)+(A(L1,K2)-A(L1,K1))*Z2/Z1
      AZ2=A(L2,K1)+(A(L2,K2)-A(L2,K1))*Z2/Z1
      ABAR=AZ1+(AZ2-AZ1)*E2/E1
C.....Parameter BBAR
      BZ1=B(L1,K1)+(B(L1,K2)-B(L1,K1))*Z2/Z1
      BZ2=B(L2,K1)+(B(L2,K2)-B(L2,K1))*Z2/Z1
      BBAR=BZ1+(BZ2-BZ1)*E2/E1
C.....Mass Energy Absorption Coefficient for the Water
      XMUEN=XME(L1)+(XME(L2)-XME(L1))*E2/E1
C.....BERGER'S BUILDUP FORMULA
      BLD1=BBAR*TMFP
      BLD2=EXP(BLD1)
      BLD=1.0+ABAR*TMFP*BLD2
      RETURN
      END
C*********************************************************************C
```

Common Part INVAG.FOR

```
C*********************************************************************C
C                                                                     C
C        COMMON PART INVAG.FOR - COMPUTER PROGRAM GRDOSER             C
C                                                                     C
C*********************************************************************C
      IMPLICIT REAL*8 (A-H)
      IMPLICIT REAL*8 (O-Z)
C=====================================================================C
      PARAMETER(        ID=22
     +,                 JD=7
     +,                 NS=16
     +,                 NL=4
     +,                 NP=3
     +,                 NVS=1                                  )
```

```
C=================================================================C
      CHARACTER *10 TITLE1
      CHARACTER *12 TITLE2
      COMMON /SOURCER/TITLE2(NVS),EP(NP),YLD(NP),VOSO(ID,JD),
     +               VOSOM(ID,JD,NVS)
      COMMON /DOUBBLE/GA,TF,FLUX,XKERN,DOSET,DOSE(NVS),TDOSE
      COMMON /SOURCEI/NPS(NVS),NPI(NVS),NPF(NVS)
      COMMON /BLDFACR/ZBAR,ENERGY,TMFP,BLD,XMUEN,
     +               Z(4),E(21),XME(21),A(21,4),B(21,4)
      COMMON /LAYERSR/TITLE1(NL),ZEFF(NL),RL(NL),XLAC(NP,NL)
      COMMON /CONTRLR/XINIT,XIFIN,XDET,RDET
      COMMON /CONTRLI/INIT,IFIN,M1,NSD2,IFLAG1,IFLAG2
      COMMON /INTERSR/A1(JD,NS),B1(JD,NS),DIST1(JD,NS,NL),
     +               DIST2(JD,NS,NL)
      COMMON /GEOMETR/X(ID),Y(JD),XCV(ID),ARX(JD)
C*****************************************************************C
```

GRDOSER.INP Input File

Comments were inserted into the GRDOSER.INP input file to identify the variables and to show the sequence in which they are incorporated into the program. Integer and real variables are read in free format. The characters TITLE1 and TITLE2 are read in specific formats.

The GRDOSER.INP file presented below has only illustrative purposes. The inserted comments (i.e., the comments identified by C...) must be removed before using it to provide the data shown in the GRDOSER.OUT output file. It is important to review the subroutine INPUT before reading the GRDOSER.INP file.

```
C...GRDOSER.INP input file

C...Length of the pipe--INIT, IFIN, XINIT, and XIFIN
C...(free format)

7       21       3.0       12.0

C...Position of the detector--XDET and RDET
C...(free format)

7.50     1.00
C...
C...Identification of the materials of the layers--TITLE1(NLC)
C...(format(A10))
```

```
C...
AIR
IRON
CONCRETE
AIR

C...Effective atomic numbers and outer radii for the layers
C...--ZEFF(NLC) and RL(NC)
C...(free format)

8.0       0.05
26.0      0.057
11.0      0.257
8.0       1.00
C...
C...Identification of the radionuclides--TITLE2(NVSC)
C...(format(A12))
C...
NITROGEN-16

C...Number of gamma rays per radionuclide--NPS(NVSC)
C...(free format)

3

C...Energies of the gamma rays--EP(NPC)
C...(free format)

2.75  6.13  7.11

C...Yields of the gamma rays--YLD(NPC)
C...(free format)

0.01  0.69  0.05

C...Linear attenuation coefficient for each gamma ray
C...in each layer--XLAC(NPC,NLC)
C...(free format)

0.00445  29.5536  9.04163  0.00445
0.00294  23.9341  6.28331  0.00294
0.00277  23.5804  5.99544  0.00277

C...Effective atomic numbers for buildup calculations--Z(NZC)
C...(free format)

         8.0       11.0      26.0      82.0

C...Energies and parameters a for buildup calculations using
C...Berger's formula--E(NEC) and A(NEC,NZC)
C...(free format)

 0.04    2.58       0.26      0.02      0.01
 0.05    4.36       0.52      0.04      0.01
 0.06    5.59       0.78      0.07      0.01
 0.08    6.47       1.42      0.14      0.02
 0.1     6.11       1.83      0.24      0.20
 0.15    4.88       2.19      0.52      0.21
 0.2     4.13       2.20      0.77      0.08
 0.3     3.18       2.03      1.06      0.08
 0.4     2.67       1.87      1.15      0.11
 0.5     2.32       1.73      1.16      0.15
```

```
 0.6      2.07        1.60        1.14        0.19
 0.8      1.74        1.41        1.09        0.25
 1.0      1.50        1.27        1.03        0.30
 1.5      1.16        1.02        0.88        0.36
 2.0      0.97        0.89        0.76        0.38
 3.0      0.74        0.71        0.66        0.37
 4.0      0.62        0.59        0.56        0.31
 5.0      0.52        0.49        0.49        0.24
 6.0      0.47        0.45        0.42        0.19
 8.0      0.38        0.36        0.33        0.11
10.0      0.31        0.30        0.25        0.07

C...Parameters b for buildup calculations using Berger's
C...formula--B(NEC,NZC)
C...(free format)

          0.024      -0.035      -0.032      -0.066
          0.057      -0.026      -0.034      -0.046
          0.082      -0.008      -0.039      -0.028
          0.108       0.007      -0.034      -0.029
          0.120       0.028      -0.030       0.479
          0.125       0.054      -0.015      -0.075
          0.118       0.065       0.004      -0.054
          0.096       0.067       0.022      -0.040
          0.080       0.061       0.033      -0.033
          0.068       0.055       0.036      -0.028
          0.059       0.049       0.036      -0.024
          0.045       0.040       0.032      -0.019
          0.036       0.032       0.028      -0.015
          0.021       0.021       0.020      -0.007
          0.013       0.014       0.018       0.004
          0.005       0.007       0.014       0.019
          0.000       0.004       0.015       0.038
         -0.002       0.004       0.017       0.062
         -0.005       0.002       0.021       0.082
         -0.006       0.001       0.028       0.125
         -0.005       0.003       0.039       0.161

C...Mass energy absorption coefficients for the water
C...--XME(NEC)
C...(free format)

0.00620  0.00383     0.00296     0.00249     0.00248
0.00274  0.00295     0.00319     0.00328     0.00331
0.00328  0.00319     0.00310     0.00283     0.00260
0.00227  0.00207     0.00192     0.00181     0.00167
0.00158

C...End of file
```

GRDOSER.OUT Output File

```
**********************************************************************

OUTPUT FROM THE COMPUTER PROGRAM GDOSER
UNIVERSITY OF FLORIDA
DEPARTMENT OF NUCLEAR ENGINEERING SCIENCES
S. Gavazza - 1992
```

****

GAMMA RAY DOSE EQUIVALENT RATE FROM THE
MOVING RADIONUCLIDES INSIDE THE PIPE

FLUID AND DIMENSIONS OF THE SHIELDED PIPE
Fluid= AIR
Inner Radius= .0500m
Length: XINIT= 3.0000m XIFIN= 12.0000m

POSITION OF THE DETECTOR
XDET= 7.5000m RDET= 1.0000m

MULTILAYERED SHIELD

Layer	Material	Zeff	Outer Radius(m)
1	AIR	8.0	.0500
2	IRON	26.0	.0570
3	CONCRETE	11.0	.2570
4	AIR	8.0	1.0000

RADIONUCLIDE, GAMMA RAYS, ENERGIES(MeV), YIELDS
NITROGEN-16
GAMMA 1: 2.7500 .0100
GAMMA 2: 6.1300 .6900
GAMMA 3: 7.1100 .0500

MATERIALS, GAMMA RAYS, LINEAR ATTEN. COEF.(1/m)
AIR
GAMMA 1: .00445
GAMMA 2: .00294
GAMMA 3: .00277
IRON
GAMMA 1: 29.55360
GAMMA 2: 23.93410
GAMMA 3: 23.58040
CONCRETE
GAMMA 1: 9.04163
GAMMA 2: 6.28331
GAMMA 3: 5.99544
AIR
GAMMA 1: .00445
GAMMA 2: .00294
GAMMA 3: .00277

BERGER'S PARAMETERS FOR BUILDUP CALCULATIONS

ENERGY (MeV)	ZEFF VALUES 8.0	11.0	26.0	82.0
Parameter a				
.040	2.5800	.2600	.0200	.0100
.050	4.3600	.5200	.0400	.0100
.060	5.5900	.7800	.0700	.0100
.080	6.4700	1.4200	.1400	.0200
.100	6.1100	1.8300	.2400	.2000
.150	4.8800	2.1900	.5200	.2100
.200	4.1300	2.2000	.7700	.0800
.300	3.1800	2.0300	1.0600	.0800
.400	2.6700	1.8700	1.1500	.1100
.500	2.3200	1.7300	1.1600	.1500
.600	2.0700	1.6000	1.1400	.1900
.800	1.7400	1.4100	1.0900	.2500
1.000	1.5000	1.2700	1.0300	.3000

1.500	1.1600	1.0200	.8800	.3600
2.000	.9700	.8900	.7600	.3800
3.000	.7400	.7100	.6600	.3700
4.000	.6200	.5900	.5600	.3100
5.000	.5200	.4900	.4900	.2400
6.000	.4700	.4500	.4200	.1900
8.000	.3800	.3600	.3300	.1100
10.000	.3100	.3000	.2500	.0700

Parameter b

.040	.0240	-.0350	-.0320	-.0660
.050	.0570	-.0260	-.0340	-.0460
.060	.0820	-.0080	-.0390	-.0280
.080	.1080	.0070	-.0340	-.0290
.100	.1200	.0280	-.0300	.4790
.150	.1250	.0540	-.0150	-.0750
.200	.1180	.0650	.0040	-.0540
.300	.0960	.0670	.0220	-.0400
.400	.0800	.0610	.0330	-.0330
.500	.0680	.0550	.0360	-.0280
.600	.0590	.0490	.0360	-.0240
.800	.0450	.0400	.0320	-.0190
1.000	.0360	.0320	.0280	-.0150
1.500	.0210	.0210	.0200	-.0070
2.000	.0130	.0140	.0180	.0040
3.000	.0050	.0070	.0140	.0190
4.000	.0000	.0040	.0150	.0380
5.000	-.0020	.0040	.0170	.0620
6.000	-.0050	.0020	.0210	.0820
8.000	-.0060	.0010	.0280	.1250
10.000	-.0050	.0030	.0390	.1610

MASS ENERGY ABSORPTION COEFFICIENTES FOR WATER

ENERGY (MeV)	MEAC (m2/kg)
.040	.00620
.050	.00383
.060	.00296
.080	.00249
.100	.00248
.150	.00274
.200	.00295
.300	.00319
.400	.00328
.500	.00331
.600	.00328
.800	.00319
1.000	.00310
1.500	.00283
2.000	.00260
3.000	.00227
4.000	.00207
5.000	.00192
6.000	.00181
8.000	.00167
10.000	.00158

CALCULATION SUMMARIES

NUMBER OF CONTROL VOLUMES

x Direction	=	15
y Direction	=	5
Ang. Direction	=	16

Total = 1200

GAMMA RAY DOSE EQUIVALENT RATE

RADIONUCLIDE(s)	DER (Sv/s)
NITROGEN-16	1.3021E-09
Total	1.3021E-09

APPENDIX D
APPARATUS FOR EXPERIMENTAL MEASUREMENTS

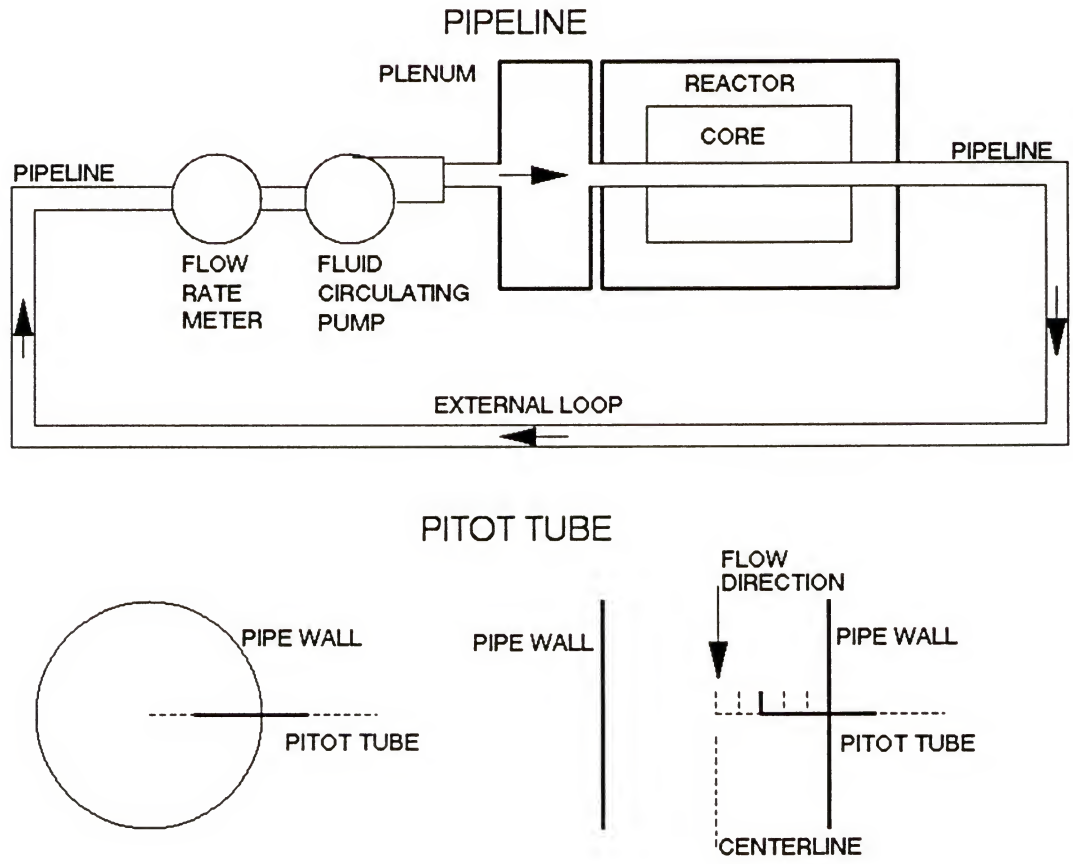


Figure D-1. Schematic diagram of an apparatus for experimental measurements (Not to scale).

REFERENCES

1. J. N. Stannard, Radioactivity and Health: A History, R. W. Baalman, Jr. (Ed.), Pacific Northwest Laboratory, Available as DE88013791 (DOE/RL/01830-T59), National Technical Information Service, Springfield, VA (1988).

2. R. D. Evans, The Atomic Nucleus, Robert E. Krieger Publishing Company, Malabar, FL (1982).

3. K. S. Krane, Introductory Nuclear Physics, John Wiley & Sons, New York, NY (1988).

4. H. Cember, Introduction to Health Physics, Pergamon Press, Oxford, England (1988).

5. "Radiological Health Handbook", Bureau of Radiological Health (Ed.), U. S. Department of Health, Education, and Welfare, Rockville, MD (1970).

6. J. E. Turner, J. S. Bogard, J. B. Hunt, and T. A. Rhea, Problems and Solutions in Radiation Protection, Pergamon Press, New York, NY (1988).

7. F. H. Attix, Introduction to Radiological Physics and Radiation Dosimetry, John Wiley & Sons, New York, NY (1986).

8. T. Rockwell III, "Reactor Shielding Design Manual," TID-7004, Naval Reactors Branch, Division of Reactor Development, United States Atomic Energy Commission, Office of Technical Services, Department of Commerce, Washington, D.C. (March 1956).

9. J. Wood, Computational Methods in Reactor Shielding, Pergamon Press, Oxford, England (1982).

10. J. G. Picarelli, "Activation of Circulating Cooling Media and Circulating Fuels," Engineering Compendium on Radiation Shielding, Vol. III, Sec. 10.10.1, R. G. Jaeger (Ed.), Springer-Verlag, New York, NY (1968).

11. S. V. Patankar and D. B. Spalding, Heat and Mass Transfer in Boundary Layers, Second Edition, Intertext Books, London, England (1970).

12. S. V. Patankar and D. B. Spalding, "A Calculation Procedure for Heat, Mass and Momentum Transfer in Three-Dimensional Parabolic Flows," Int. J. Heat Mass Transfer, Vol. 15, pp. 1787-1806 (1972).

13. S. V. Patankar, Numerical Heat Transfer and Fluid Flow, Hemisphere Publishing Corporation, New York, NY (1980).

14. S. V. Patankar, Computation of Conduction and Duct Flow Heat Transfer, Innovative Research, Inc., Maple Grove, MN (1991).

15. "microCOMPACT Version 2.1: A General-Purpose Computer Program for Two-Dimensional Fluid Flow and Heat Transfer," Innovative Research, Inc., Maple Grove, MN (1991).

16. Y. Lee, "Trajectories and Heating of Particles Injected into a Thermal Plasma," Thesis for Master of Science, University of Minnesota, MN (1982).

17. Y. Lee, "Modeling Work in Thermal Plasma Processing," Dissertation for Doctor of Philosophy, University of Minnesota, MN (1984).

18. S. Gavazza, "Calculation of Parameters of a Shielding Experiment," Thesis for Master of Science (in Portuguese), Instituto Militar de Engenharia, Rio de Janeiro, Brazil (1986).

19. N. M. Schaeffer, Reactor Shielding for Nuclear Engineers, United States Atomic Energy Commission, TID-25951, National Technical Information Service, Department of Commerce, Springfield, VA (May 1974).

20. D. Bünemann and G. Richter, "Multilayered Shields," Engineering Compendium on Radiation Shielding, Vol. I, Sec. 4.3.2, R. G. Jaeger (Ed.), Springer-Verlag, New York, NY (1968).

21. A. B. Chilton, J. K. Shultis, and R. E. Faw, Principles of Radiation Shielding, Prentice-Hall, Inc., Englewood Cliffs, NJ (1984).

22. J. J. Duderstadt and L. J. Hamilton, Nuclear Reactor Analysis, John Wiley & Sons, New York, NY (1976).

23. ANSI/ANS-6.1.1-1977, Neutron and Gamma-Ray Flux-to-Dose-Rate Factors, American National Standards Institute, Inc., New York, NY (1977).

24. ANSI/ANS-6.1.1-1991, Neutron and Gamma-Ray Fluence-to-Dose Factors, American National Standards Institute, Inc., New York, NY (1991).

25. A. Foderaro, "The Photon Shielding Manual," The Penn State Bookstore, The Pennsylvania State University, PA (April 1978).

26. E. P. Blizard, A. Foderaro, N. G. Goussev, and E. E. Kovalev, "Extended Radiation Sources (Point Kernel Integrations)," Engineering Compendium on Radiation Shielding, Vol. I, Chap. 6, R. G. Jaeger (Ed.), Springer-Verlag, New York, NY (1968).

BIOGRAPHICAL SKETCH

Sergio Gavazza was born on February 28, 1949, in Pirassununga, SP, Brazil. In December of 1970, Sergio Gavazza graduated as an army officer at the Academia Militar de Agulhas Negras (Agulhas Negras Military Academy) in Agulhas Negras, RJ, Brazil. In December of 1980, he received the degree of Bachelor of Science in fortification and construction from the Instituto Militar de Engenharia (Military Engineering Institute), in Rio de Janeiro, RJ, Brazil. He received the degree of Master of Science in nuclear engineering, with a concentration in radiation shielding, in February of 1986, from the same institute.

Sergio Gavazza worked on many projects for the Brazilian Army and taught a course on radiation shielding in the Nuclear Engineering Department of the Military Engineering Institute.

In January of 1990, he was admitted to the graduate program of the Nuclear Engineering Department at the University of Florida to pursue a Ph.D. degree, which has been sponsored by the Brazilian Army.

Sergio Gavazza has been a member of Alpha Nu Sigma, the Nuclear Engineering Honor Society, since 1991.

He is married to Neusa Zornoff Gavazza. Their daughters are Cristina, Cláudia, and Patrícia.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

David E. Hintenlang, Chairman
Assistant Professor of
Nuclear Engineering Sciences

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

William H. Ellis, Cochairman
Associate Professor of
Nuclear Engineering Sciences

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Nils J. Diaz
Professor of
Nuclear Engineering Sciences

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

William E. Bolch
Professor of Environmental
Engineering Sciences

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Luis M. Muga
Professor of Chemistry

This dissertation was submitted to the Graduate Faculty of the College of Engineering and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

December 1992

Winfred M. Phillips
Dean, College of Engineering

Madelyn M. Lockhart
Dean, Graduate School